THE DEVELOPMENT OF DESIGN PRINCIPLES FOR PREDICTING THE IGNITION PERFORMANCE OF SOLID PROPELLANT ROCKET MOTORS

NASA Grant NGR 31-001-109
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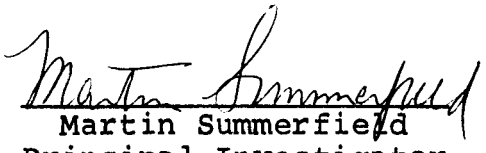
June 23, 1969

Transmitted by:



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The following staff members at Princeton University have contributed to this report:

Dr. William J. Most, former Ph.D. candidate, Assistant-in-Research, was the one who was directly responsible for much of the project, including analysis, experimentation, report writing, etc. His Ph.D. thesis was based on this project.

Mr. K. K. Kuo, Graduate Student, Assistant-in-Research, contributed the theoretical section on motors with small port-to-throat ratio. He will continue to work on this problem in the future.

Mr. B. W. MacDonald, former Undergraduate Senior, contributed to the investigation of the ignition transient of a rocket motor ignited by a pyrotechnic hot particle igniter (theory and experiment), and to the general computer program.

The project was directed by Prof. M. Summerfield. Mr. Peter L. Stang, Member of the Technical Staff, participated in the direction of the laboratory work and the test firings, and in the interpretation of results.

Mr. C. R. Felsheim carried out the processing of the solid propellant used in the program and collaborated in the development of the experimental equipment. Advice on matters of instrumentation and assistance with the experimental firing program was given by Mr. S. O. Morris. Credit for the photographic work and related areas goes to Mr. E. R. Crosby. Mr. J. H. Semler was instrumental in the fabrication of the experimental equipment.

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Introduction

This document is being submitted as the semi-annual progress report on NASA Grant NGR 31-001-109 for a research program entitled: "The Development of Design Principles for Predicting the Ignition Performance of Solid Propellant Rocket Motors". The six-month period covered in this report is October 1, 1968 to March 31, 1969. This report is organized around the six Research Objectives listed on pages 10 and 11 of our 1968-69 Proposal[1]. The proposal, as originally submitted, contemplated a higher level of funding than the sum actually granted. NASA budgeting limitations forced a 35% reduction from the cost estimate on which the set of six Research Objectives was based. Of necessity, therefore, this reduction is reflected in the reduced pace on several of the Research Objectives discussed below. However, despite the reduction in effort, substantial progress has been made on at least four of the six Research Objectives listed in the proposal. The achievements are detailed below.

Research Objective #1: Basic Mechanisms Controlling the Thrust Transient.

A large part of the effort of this program has been focused on the basic elements or mechanisms which play a role in the overall ignition transient. These studies have been carried out with a variety of techniques and instrumentation. The accomplishments to date, which have been most recently reported in Ref. 2, can be summarized as follows:

The processes of local ignition, subsequent flame spreading, and chamber gas dynamics have been studied both by high speed photography and by measurement of the chamber pressure - time history. These studies have confirmed that a diffuse but definite zone, identifiable as a flame front, does indeed propagate down the propellant surface, as the flame spreading hypothesis requires. This flame spreading is a consequence of local heating to a particular critical ignition temperature. Heat transfer studies have confirmed that, in vigorous ignition situations, the local heating is dominated by convective heat transfer from the hot gas boundary layer. There seems to be no important energy transfer from either the adjacent flame or radiation from the hot gas - at least for small motors. Calorimetric studies of the heat loss from the flowing gases, and thermocouple probing along the motor center line, both have confirmed the existence of strong axial gas phase temperature gradients during the induction interval and during the early portion of the flame spreading interval, which must be included in a complete theory.

During this report period studies have been undertaken which focus on two fundamental elements affecting the overall ignition thrust transient. The first of these studies was concerned with certain anamolies previously observed when theoretical predictions were compared to test firings of motors with marginal igniters.[2] This led to an improvement in the description of the local ignition process, as explained below. The second study was concerned with the gas dynamic model for the combustion chamber. The initial formulation of a more comprehensive model has been completed, which allows for a high subsonic Mach number in the combustion chamber. This model is capable of accurately describing a wider class of rocket motors than has heretofore been considered; it is explained later in this section.

A series of test firings of a small laboratory scale motor was carried out, in which the igniter mass flow rate was progressively decreased while the total mass delivered by the igniter was held constant. When these test firings were compared to theoretical predictions (see Research Objective No. 2 below for a discussion of the prediction method), it was found that the quality of the computer predictions degenerated for increasingly marginal ignition situations, i.e., for hangfires, although the correct trends were predicted. The theoretical predictions consistently yielded longer delays in the hangfires than were observed experimentally. This indicated that some source of energy input to the grain had not been included in the model.

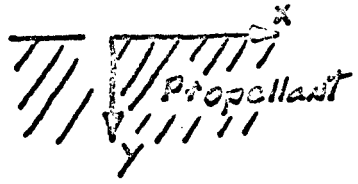
It is hypothesized that the difficulty arises in the arbitrarily simplified ignition temperature criterion. This criterion states that the propellant is completely inert thermochemically until a critical ignition temperature is reached. However, it is known that pre-ignition reactions in the gas phase and/or on the surface contribute to the heating up process[3,4,5]. This contribution turns out to be negligible in vigorous heating, rapid flame spreading situations, but it becomes significant in marginal (hangfire) cases. This heat is released close to the hot surface by the decomposing ammonium perchlorate and perhaps by interface reactions between the AP and the binder. The structure of this reaction zone is very complex; the gas phase part of it has been studied extensively in this Laboratory[6] and elsewhere in relation to the question of steady state burning mechanism. The condensed phase part of it has been studied by others. The overall energy release rate at the propellant surface (or near it), while the surface temperature is still below the ignition temperature, is described in this work for convenience in a very approximate way by:

$$\dot{q}_{surface} = \rho_p Q r = \rho_p Q A e^{-E_s/RT_s}$$

where ρ_p is the propellant density, Q is the heat release per unit mass and the pre-exponential, A, has the dimensions of burning rate. This expression implies that the integrated

effect of heat release below, at, and above the propellant surface is assigned to the surface. This simplification allows the nonlinear term representing the distributed heat release to be taken out of the solid phase heat diffusion equation and placed in the boundary condition.

$$\frac{\partial T}{\partial t} = \alpha_p \frac{\partial^2 T}{\partial y^2}$$



$$T(x,y,0) = T_0$$

$$T(x,\infty,t) = T_0$$

$$\left(\lambda_p \frac{\partial T}{\partial y}\right)_{y=0} = -\left[\dot{q}_{surf}(x,t) + \dot{q}_{gas}(x,t)\right]$$

The effect of this term is dramatically shown in Fig. 1 for a marginal ignition situation. The values of the activation energy, E_s, and the heat release parameter were obtained by selecting those values which brought the theoretical predictions into agreement with the experimental firings for Runs C-1, C-2 and C-3 shown in Fig. 2. This may appear to be a crude approach, merely empirical. However, the necessary physical parameters are not well known for steady state cases, and they certainly are not available for incipient transient cases. Thus, a certain amount of curve fitting is justified. The activation energy and surface heat release found in this way are within approximately 10% of the quoted steady state values[6]. The values which gave the best fit for all three runs, C-1, C-2 and C-3, are E_s = 13,700 cal/mole, and Q = 250 cal/gram. The appropriate value for A was found by matching the measured regression rate to the regression rate calculated with the expression $r = A e^{-E_s/RT_s}$ using this value of E_s and the steady state value of T_s.

It is important to re-emphasize that this self-heating term is important only in marginal ignition situations. The proper trends would be predicted even without this term. Thus, as the conditions for a hangfire are approached, the designer would be warned by the analysis that the igniter is marginal, even if detailed agreement between the prediction and a test firing is not achieved.

The gas dynamic model for the combustion chamber of a solid propellant rocket motor during the thrust transient[1,7,8] which has been previously developed on this program contains several restrictive assumptions. This analytical description most closely models the class of rocket motors with large port-to-throat area ratios, which are ignited by gas-producing igniters located in the forward end of the

engine. This class of motors does not suffer significant axial pressure and temperature gradients down the motor port. The kinetic energy of the gases in the port of such motors can be neglected compared to the thermal energy terms, and the momentum change associated with mass addition can be neglected. In rocket motors with small port-to-throat area ratios these approximations are not valid. A more elaborate analysis which avoids these restrictions has been formulated. The details of this work are given in Appendix A. Efforts are currently being directed toward solving this model. Research on the basic processes controlling the ignition transient will be continued, with theoretical work on the new gas dynamic model and with experiments on a small port-to-throat area ratio motor.

Research Objective #2: Development of Thrust Transient Computer Prediction Methods.

Over the past five years an analytical model for predicting the entire ignition thrust transient in a solid propellant rocket motor has been developed[1,7,8]. This theoretical model is most directly (but not exclusively) applicable to the class of motors with large port-to-throat area ratios, which are ignited by pyrogen igniters located in the forward end of the engine. The essential elements of the theoretical model can be summarized as follows:

The local ignition event is characterized by a constant critical surface temperature ignition criterion and by the inclusion of a surface heat release term to account for exothermic decomposition at temperatures below the critical temperature. Flame spreading is described by coupling this ignition model with an experimentally measured description of the gas phase heat convection to the propellant grain. The propellant burning rate after ignition is achieved is taken as the steady state burning rate. The analytical model is completed by describing the bulk gas dynamics of the combustion chamber by writing the dynamic energy and mass continuity equations. The resulting system of equations can be solved analytically only under very restrictive assumptions. For example, if it is assumed that flame spreading is complete, that the igniter flow is terminated and that the chamber temperature is constant, the equation for the chamber pressure as a function of time can be solved analytically. However, in the majority of interesting cases such simplifications are not possible and recourse to digital computer solution is necessary.

Toward this end a computer program has been developed. Actually two programs have been developed: The first is based on a burning rate expression of the form $r = kp_c^n$; the second program can handle more complicated burning rate expressions, even from tabular r vs p data. This second program is also capable of handling nonsteady burning rate equations.

The programs are written in Fortran IV and thus are compatible with any Fortran IV compiler. Most of the work in this study has been run on an IBM 360 computer.

During this report period an effort has been made to upgrade the programs with two prime objectives in mind: first, that program execution time be kept to a minimum without sacrificing accuracy, and second, that the program be completely self-explanatory in order to facilitate its use. For example, in regard to the first goal, the heat transfer calculations are the most time-consuming operation - particularly when the nonlinear exponential self-heating term is included. In an effort to reduce the execution time, a study was undertaken which indicated that the self-heating term does not become important until the surface temperature is within 40% of ignition temperature. Thus, the calculation need not be performed until this temperature is reached, and as a result, a great deal of time is saved. As a consequence of this and similar studies, the execution time for the prediction of a normal vigorous ignition is less than 4 minutes, with 45 seconds of this being compilation time. Thus, maximum efficiency is achieved when several predictions are run at the same time, thereby eliminating the compilation time for each run. Computer predictions of long-delay hangfire cases require substantially more time than for vigorous ignition cases.

In an effort to make the program completely self-explanatory, the program contains a complete table of nomenclature. Liberal use of comment cards throughout the program supply guides to the computer logic.

Appendix B contains a detailed discussion of the system of equations to be solved, the numerical techniques used and input instructions. Complete listings of the two programs and a program flow chart are also given.

It is important that any potential user of such a computer program be aware of the sensitivity of the calculations to various input data. In the case of the ignition transient prediction program, two important input parameters are the propellant ignition temperature and the thermal conductivity. These values are often not known with great accuracy. In order to test the sensitivity of the computer program to these parameters, a computer study was undertaken wherein the values were varied within reasonable limits. As might be anticipated, the model is more sensitive to small uncertainties in these parameters in marginal ignition situations than in vigorous ignition cases. The standard deviation in the experimental determination of the ignition temperature was $\pm$ 15°C [9]. In order to test the effect of this uncertainty, the ignition temperature was varied by $\pm$ 20°C, both for vigorous and marginal cases. The results are shown in Fig. 3. The effects of varying the thermal conductivity by $\pm$ 10% for both cases are shown in Fig. 4. The extreme sensitivity of the computer program to the ignition temperature and the thermal conductivity must be kept in mind when it is apparent that a marginal situation is being approached.

Research Objective #3: Systematic Test Firing Series to Test the Validity of the Design Rules.

Three experimental test firing series have been previously reported on this research program[1,7,8]. In each series a single experimental parameter was systematically varied with all other parameters held constant. In Series A the exhaust nozzle was varied, in Series B the igniter duration was varied, and in Series C the igniter mass flow rate was varied with the total igniter mass held constant. The excellent agreement between the theoretical predictions and the experimental test firings for the vigorous ignition situations of Series A and B was most recently reported in our 1968-1969 proposal. The procedure for correction of the theoretical predictions by including the effect of heat generation in the condensed phase, in the form of a surface heat release term, was reported above in Research Objective 1 for the marginal ignition cases of Series C.

During the past report period two additional test firing series have been performed. The first of these, Series D, is a study of marginal igniter durations. The second, Series E, shows the effect of aluminum addition to the propellant. Since the latter Series is an extension of the prediction theory to a new class of propellants, Series E is reported under Research Objective 6.

Series D (Fig. 5) was originally intended to display the effects of varying the size of the motor exhaust nozzle systematically, while other design parameters were held constant. This is similar to Series A[1,2]. The difference was to be that the pressure overshoots observed in Series A would be eliminated. A choice was made of the magnitude and duration of the igniter flow, and these were held constant.

The systematic variation of nozzle throat diameter, from small to large, was expected to show corresponding systematic changes in the final equilibrium pressure, from high to low. It can be seen in the pressure-time traces of this series, that this expectation was fulfilled.

However, some irregular behavior showed up in the traces for the firings with the largest nozzles. Upon examination of this situation, it was concluded that this resulted from the choice of an igniter input (mass flow and duration) that was very close to the marginal requirement for prompt ignition. Under such circumstances, while the firings with the smaller nozzles resulted in acceptable pressure-time traces, the firings with the larger nozzles showed erratic behavior indicative of an ignition input that is marginal.

Further verification of the interpretation, that this particular choice of igniter flow and duration was marginal, was provided by the appearance of some unexpected hangfires in the Series during the test firing program. These

unexpected hangfires are shown in Fig. 6. There was no change in the firing conditions for the traces shown in Fig. 6 as compared with the traces shown in Fig. 5. The interpretation is clear, that the ignition exposure was marginal. As may be expected in a marginal situation, the firing behavior is sometimes normal, and in such normal situations, it was found that the experimental firing trace came close to the theoretical prediction for that situation. Such agreement is shown in Fig. 7.

That the chosen exposure was indeed marginal was demonstrated theoretically by carrying out the computer prediction with a 10% smaller igniter mass flow than that standardized for Series B. The drastic effect of so small a reduction in the igniter mass flow is shown in Fig. 8. The standard exposure is computed to produce a normal ignition; however, the 10% weaker exposure results in a hangfire. It is obvious that the chosen mass flow and duration were marginal for this motor.

From observation of the normal-appearing curves in Fig. 5, it appears that enlargement of the exhaust nozzle does not stretch out the induction period, but it slows down the rise of pressure from the start of the grain burning to the final equilibrium level. That the induction period is unaffected by enlargement of the exhaust nozzle follows theoretically from the fact that the heat flux in the pre-ignition interval is not dependent on the pressure level, as long as the mass flow through the port is held fixed. The slowing down of the rise of pressure after the induction interval results from the lower rate of burning associated with the enlarged exhaust nozzle.

Additional systematic test firing series had been planned for the current year when the 1968-69 proposal was written. However, the funding cut-back forced a reduction in manpower and a proportionate reduction in effort on this item.

Research Objective #4: Analysis of Rocket Engines Produced and Tested by the Rocket Industry.

This portion of the research program has been dormant during the current year as a result of the funding cut-back. However, previous work on two practical rocket engines can be summarized.

The theoretical model of the ignition transient was tested on the 120-inch diameter rocket motor used on the Titan III-C Booster. The transient pressure-time record of this motor has been published in the open literature[10]. The prime contractor for this motor, UTC, supplied us with design information - free volume, throat area, etc. - and with the burning rate expression for the propellant used. As a result of the 5-segment design of this motor, there are five grain leading edges, one for each segment. Each pair of segments is separated by a stagnant annulus, one side of which is inhibited while the other side is allowed to burn. This geometry obviously results in a complex heat transfer -

flame spreading situation. No single heat transfer correlation would adequately describe both the motor port and the stagnant annuli. The other missing pieces in the puzzle were the details of the igniter mass flow-time history. Thus, in order to proceed an approximation was necessary. It was shown in previous work[9] that if the igniter flow is small compared to the mass addition from the burning surface, the end of flame spreading and the beginning of chamber filling can be determined graphicly. This is done by plotting $\ln(1-p^{1-n})^{-1}$ vs τ, where p and τ are the nondimensional chamber pressure and time respectively, and n is the burning rate exponent. The beginning of chamber filling is the point at which this curve becomes linear. This analysis is shown in Fig. 9. This analysis supplies the initial conditions for predicting the chamber filling interval. Despite the many approximations made in this theoretical model, the agreement between the theoretical prediction and the actual test firing is very good, as is shown in Fig. 10. The agreement is well within the design specification limits.

The second industry-developed motor studied was one developed by Frankford Arsenal (Fig. 11). The grain configuration in this motor is a hollow cylinder with tapered ends. This grain design produces neutral burning. The nozzle configuration consists of four small nozzles spaced around the base plate.

The igniter used with this motor was considerably different from any of those previously studied. This engine uses a pyrotechnic igniter system consisting of a "piccolo" tube extending down the center of the grain. Thirty-two holes in the tube permit the igniter combustion products to impinge directly on the grain. The igniter material is a mixture of magnesium and Teflon in pellet form. The principal combustion products are $MgF_2(c)$ and $MgF_2(\ell)$, with Mg(g) as the carrier gas. This is a typical "hot particle" pyrotechnic igniter.

The simplest assumption that can be made to adapt the present analytical model to this obviously different situation is to assume that the flame spreading is instantaneous. This particular motor is singularly suited to this assumption since the igniter tube extends the entire length of the grain. This brings most of the propellant surface area under direct impingement. Experiments were performed to gain knowledge of the percentage of the propellant surface which was initially covered by impinging igniter products. These tests, done by firing the igniter onto an inert grain, confirmed that most of the surface was indeed subjected to direct impingement, except for a small region in the head end of the motor. This uncovered area constituted approximately 12% of the total grain surface area. The quality of the limiting assumption of instantaneous flame spreading can be judged by comparison of the theoretical prediction and an experimental test firing of a live grain.

Another necessary piece of information was the flow rate versus time characteristics of the piccolo tube two-phase flow igniter. Based on tests made by firing the igniter into an inert chamber, the curve of gas-phase mass flow shown in Fig. 12 was adopted.

The comparison of the theoretical prediction and an experimental test firing is shown in Fig. 13. The agreement is surprisingly close. The assumption of instantaneous flame spreading dictates that the initial rate of pressurization should be higher than that which is observed experimentally, since $(dp/dt)_{max}$ is known to occur at the end of flame spreading. This assumption also dictates that the theoretical dp/dt must be lower at some later time than the experimental value. This behavior is, in fact, seen in Fig. 13.

The error in predicting the time of maximum pressure and the "saddle" in the experimental curve can be attributed to the flame spreading into the stagnant region mentioned above. Ways to allow for this effect a priori in future designs can be visualized. The 8% difference between the theoretical and experimental peak pressure is due to a probable underestimate of the pressure contribution of the vapor-particle mixture during the live motor firing, as compared to the calibration firing of the igniter into an inert chamber mentioned above.

The encouraging result of this study is that useful theoretical predictions of the ignition transient can be made for complex engines by using even the simplest assumptions, providing the gas dynamics are adequately described.

More details on this work are given in a separate report, written by B. W. MacDonald, et al., which is to be transmitted shortly, as soon as printing is complete.

Research Objective #5: Measurement of Thrust Transients as Against Simple Pressure Transients.

For the class of rocket motors with large port-to-throat area ratios, the chamber pressure is spatially uniform. Thus, the chamber pressure history together with the nozzle thrust coefficient gives the thrust history directly. The calculation is more complex for the two-phase flows arising from aluminized propellants and/or metallized igniters, but still, the chamber pressure trace gives the thrust prediction fairly directly. In the case of practical engines with small port-to-throat area ratios, however, the thrust-time traces during the start may not follow the pressure-time traces, due to the presence of strong axial pressure gradients. In order to study this, one of the test stands will be fitted with the necessary mounting brackets and the special high speed thrust instrumentation for high resolution measurements of the starting thrust transient. These measurements will use an experimental motor currently being developed. This new motor was mentioned in Research Objective #1 above. We plan to make these tests later in the contract year; they have not been done yet.

Research Objective #6: Extension of the Prediction Theory to Various Classes of Propellants.

In this portion of the research program, the effect on the ignition transient of adding aluminum powder to the propellant was studied. (Fig. 14.) One way in which such an addition could conceivably affect the ignition transient would be for the molten aluminum liberated from the first portion of the grain to be ignited to enhance the flame spreading rate downstream by impinging on the still unignited portion of the grain. We have studied this question with the aid of high speed photographs of flame spreading over an aluminized grain. Particles of molten aluminum can be seen rising from the ignited portion of the grain and entering the main gas stream. Many particles are seen actually rolling down the propellant surface. In general, those particles that hit the unignited surface do not attach themselves there or cause any significant spread of ignition as they travel downstream. In short, the movement of the flame front is determined by the overall heat transfer and not by just the hot particles, and so the flame spreading over an aluminized propellant is very similar to flame spreading over an unaluminized propellant. The quantity of hot aluminum particles liberated from the grain is not sufficient to augment significantly the spread of ignitedness.

A more detailed investigation was made on a quantitative basis. If one sets aside, for the moment, possible unpredictable combustion effects caused by aluminum, the presence of powdered aluminum may be expected to affect the pressure-time trace in several predictable ways. The first, and most obvious, is that the presence of powdered aluminum increases the thermal diffusivity of the solid propellant; this would act to slow down the rise of surface temperature at any given point on the propellant grain, and thus, slow down the rate of flame spreading. In addition, the presence of aluminum changes both the burning rate and the pressure exponent. What these changes are depends, for example, on whether the aluminum is added at the expense of ammonium perchlorate, at the expense of fuel, or at the expense of both, and on other details of difference between the aluminized and unaluminized propellants being compared. For the comparative firings reported in this report, the aluminum was added largely at the expense of the perchlorate, although some of the fuel was also removed. The burning rate exponent was depressed from 0.40 to 0.27 in the range of pressure applicable to this transient. At the same time, a significant change was observed in the burning rate of the propellant (measured in a strand burner), the value rising from 0.09 in/sec at the pre-ignition pressure of 40 psia in the unaluminized case to 0.12 in/sec at the same pressure for the aluminized propellant. Thus, the addition of aluminum made the propellant burn more actively in the lower range of pressure corresponding to the pre-ignition interval.

In the particular test firing comparison reported in this progress report, the effects of both increased thermal diffusivity and increased burning rate are observed. As seen from the theoretical predictions shown in Fig. 15, the induction period is lengthened for the aluminized propellant due to higher propellant conductivity but the higher burning rate results in a greater dp/dt. Thus, equilibrium conditions are reached earlier despite the later start.

Firing E-1 (Fig. 14), requires some additional explanation. The larger-than-normal divergence between the theoretically predicted and experimentally observed behavior is not due to any breakdown of the model because of the presence of aluminum. The earlier-than-expected pressure rise is attributed to progressive plugging of this small nozzle as the aluminum oxides condensed on the nozzle. It was difficult to identify an equilibrium pressure on the firing trace because the pressure continued to rise rapidly until the grain was consumed. After the test firing, an aluminum oxide "mold" of the nozzle was found in the motor. This confirmed the suspicion that the effective throat area was decreasing during the test firing. Repeated test firings failed to eliminate this difficulty. This behavior was not observed in test firings with larger nozzle throat diameters.

The original proposal contemplated the testing of additional classes of propellants. This will be done as rapidly as progress with the present reduced staff will permit.

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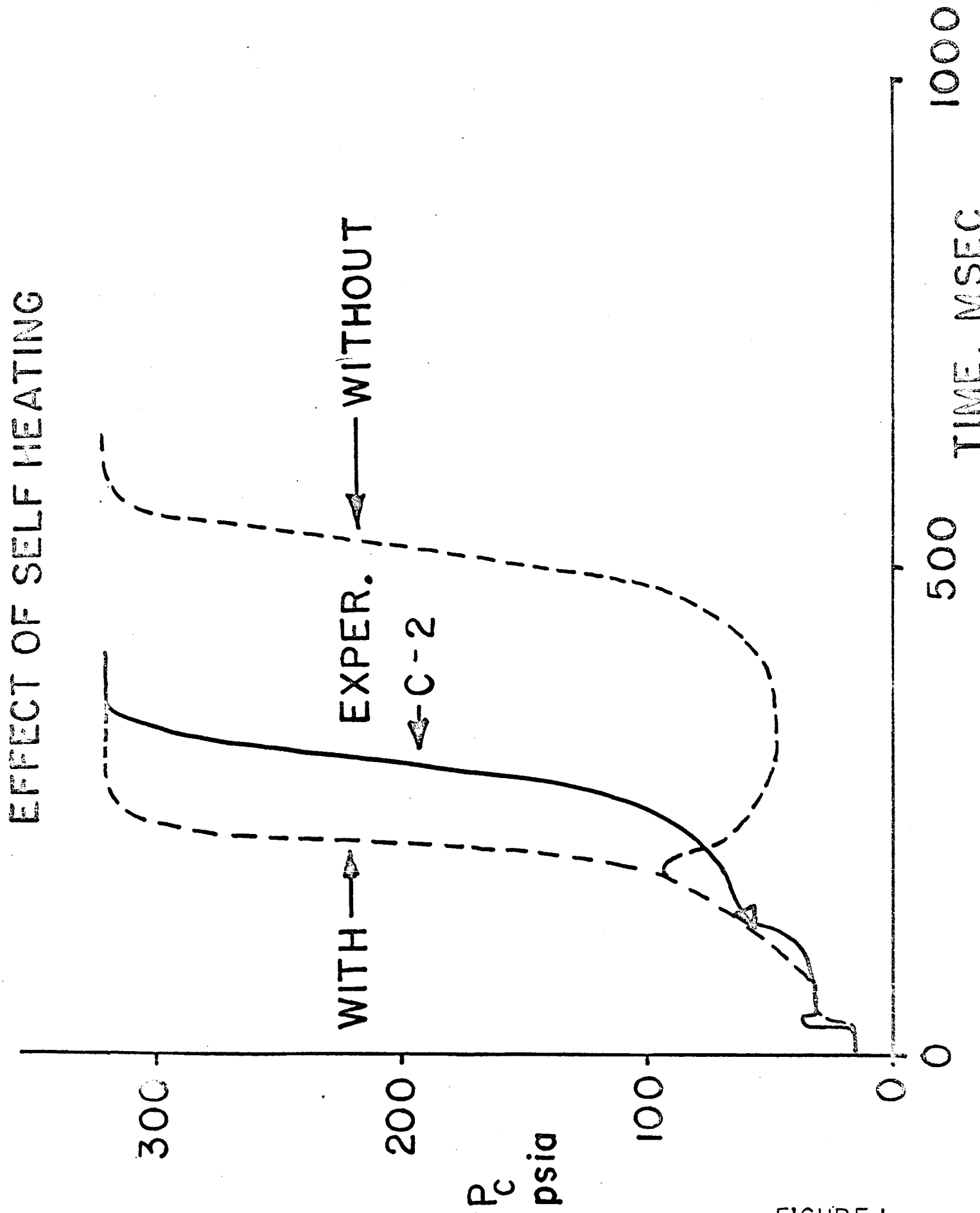

EFFECT OF SELF HEATING
WITHOUT
EXPER.
C-2
WITH
300
200
100
0
P_c psia
0
500
1000
TIME, MSEC

FIGURE I

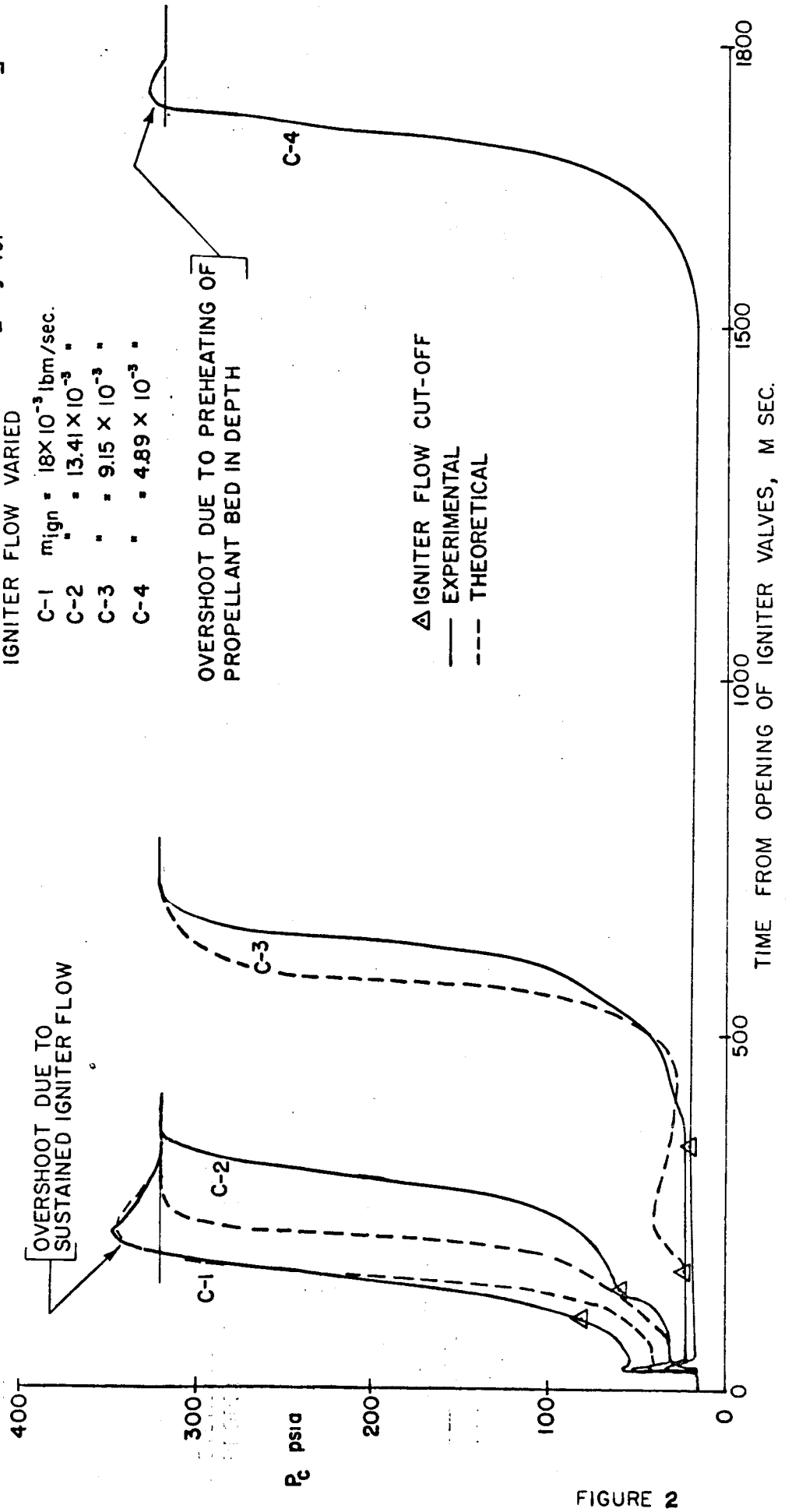

SERIES C – FIXED EXHAUST NOZZLE (d_t = .189 in.)
FIXED TOTAL IGNITER/MASS $[(m_{ign})_{Tot} = 1.44 \times 10^{-3}$ lbm]
IGNITER FLOW VARIED
C-1 $m_{ign} = 18 \times 10^{-3}$ lbm/sec.
C-2 " = 13.41×10^{-3} "
C-3 " = 9.15×10^{-3} "
C-4 " = 4.89×10^{-3} "
OVERSHOOT DUE TO PREHEATING OF PROPELLANT BED IN DEPTH
OVERSHOOT DUE TO SUSTAINED IGNITER FLOW
C-1
C-2
C-3
C-4
Δ IGNITER FLOW CUT-OFF
EXPERIMENTAL
THEORETICAL
P_c psia
400
300
200
100
0
0
500
1000
1500
1800
TIME FROM OPENING OF IGNITER VALVES, M SEC.

FIGURE 2

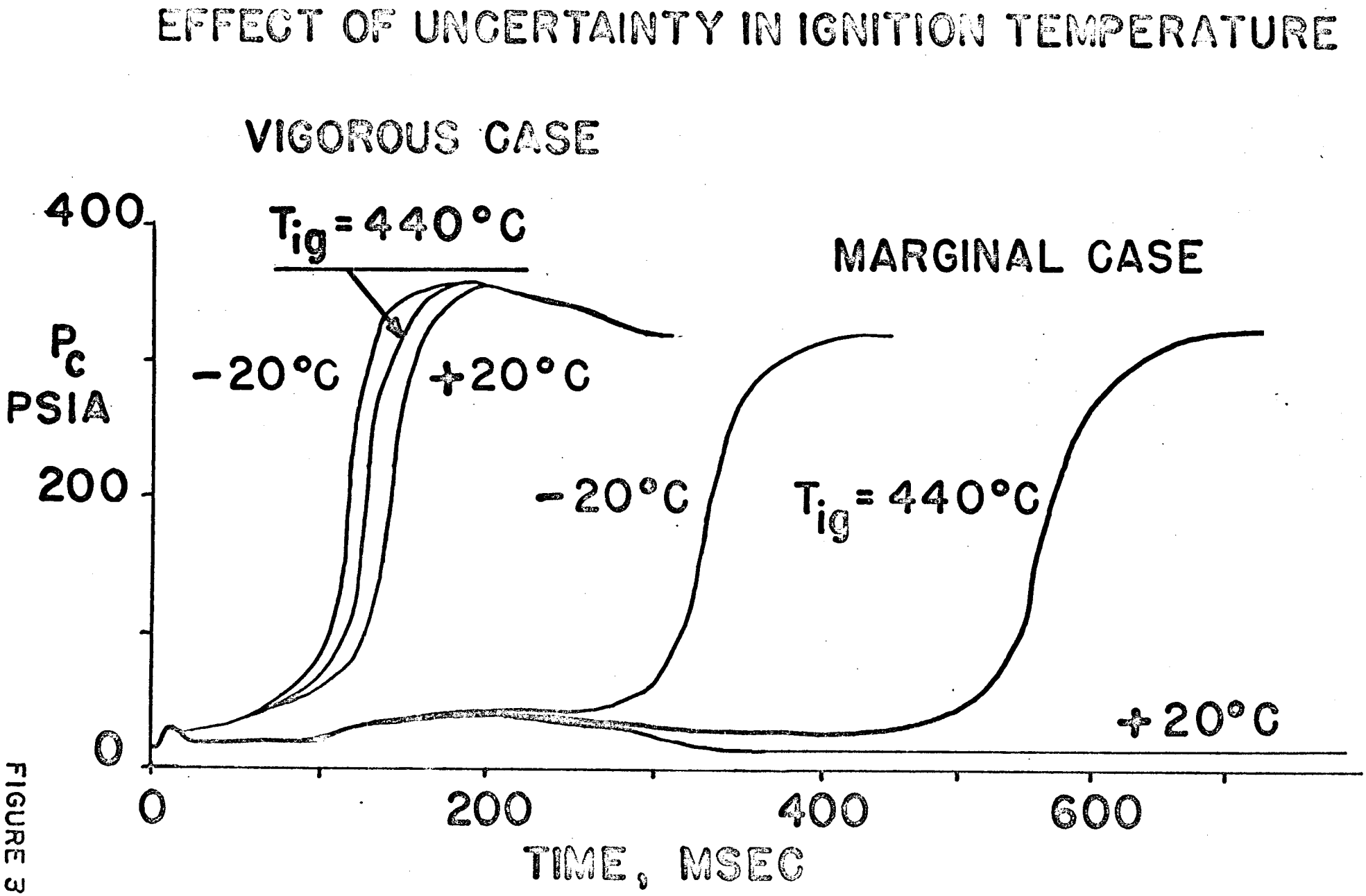

EFFECT OF UNCERTAINTY IN IGNITION TEMPERATURE
VIGOROUS CASE
400
T_{ig} = 440°C
MARGINAL CASE
P_c
PSIA
-20°C
+20°C
200
-20°C
T_{ig} = 440°C
+20°C
0
0
200
400
600
TIME, MSEC

FIGURE 3

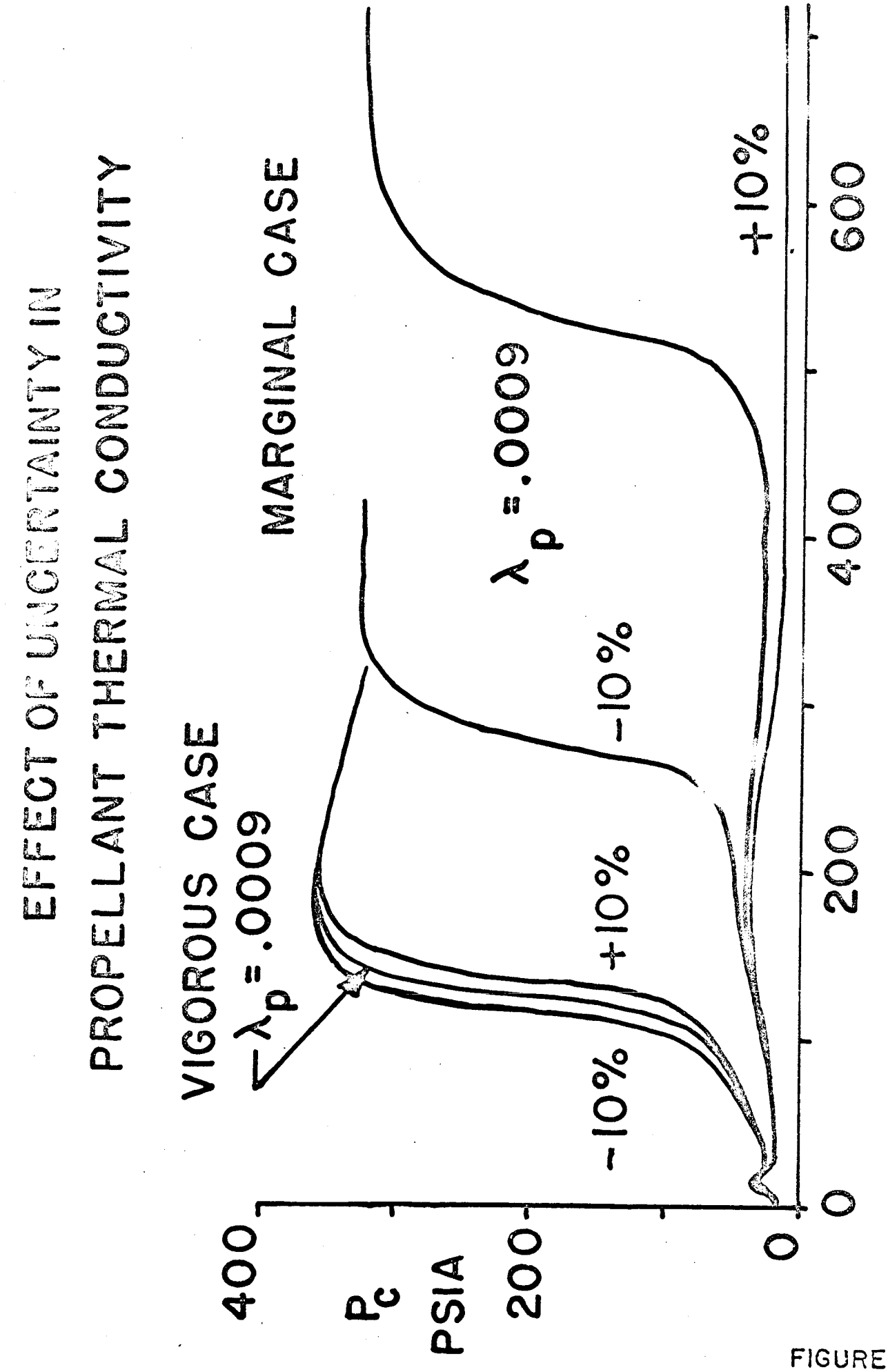

EFFECT OF UNCERTAINTY IN
PROPELLANT THERMAL CONDUCTIVITY
VIGOROUS CASE
λ_p = .0009
MARGINAL CASE
λ_p = .0009
-10%
+10%
-10%
+10%
400
200
0
P_c
PSIA
0
200
400
600
TIME, MSEC

FIGURE 4

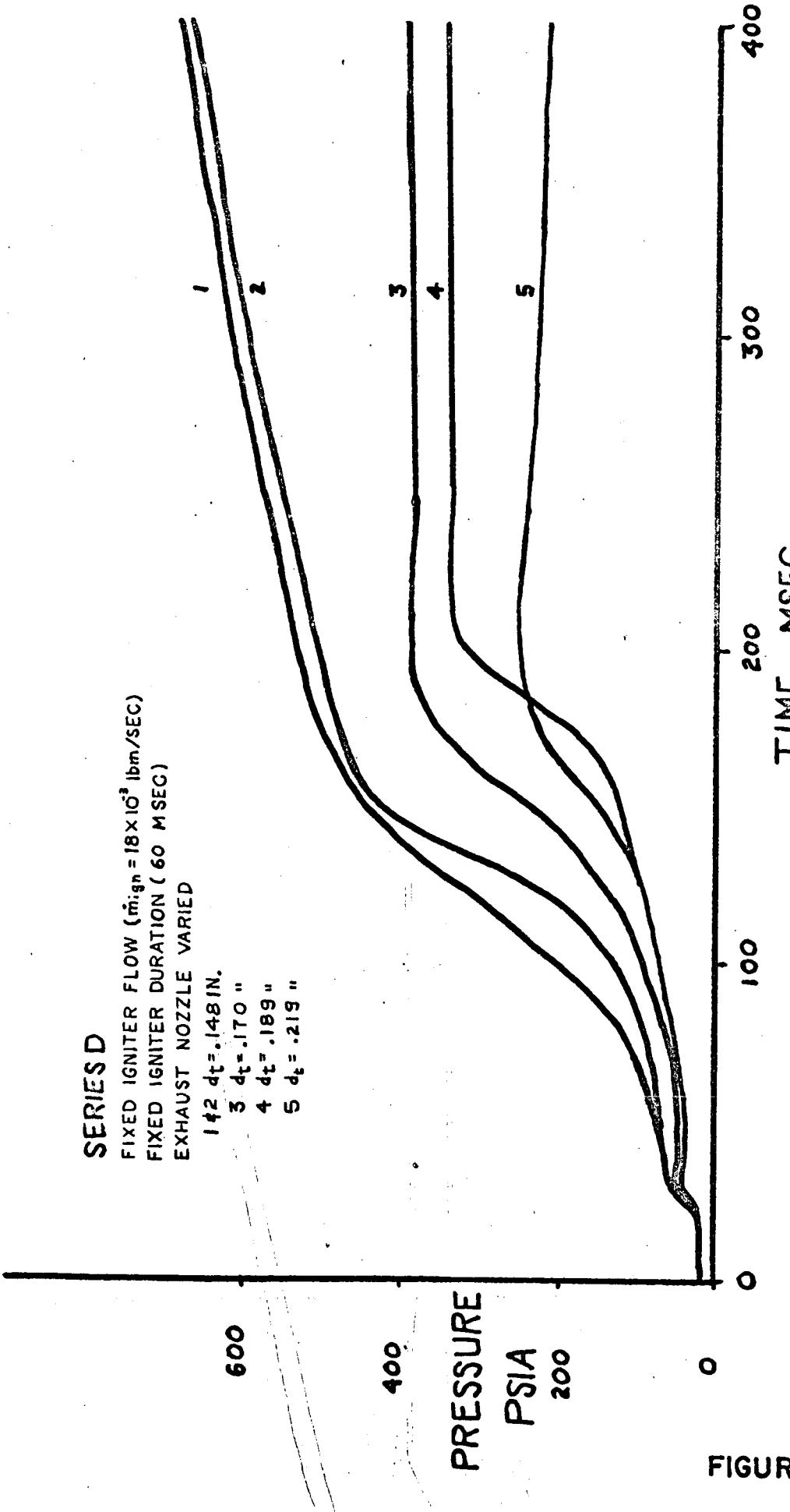

AP 26 R 4196 68
SERIES D
FIXED IGNITER FLOW ($\dot{m}_{ign}$ = 18 x 10³ lbm/SEC)
FIXED IGNITER DURATION (60 M SEC)
EXHAUST NOZZLE VARIED
1 & 2 d_t = .148 IN.
3 d_t = .170 "
4 d_t = .189 "
5 d_t = .219 "
PRESSURE PSIA
600
400
200
0
0
100
200
300
400
TIME MSEC

FIGURE 5

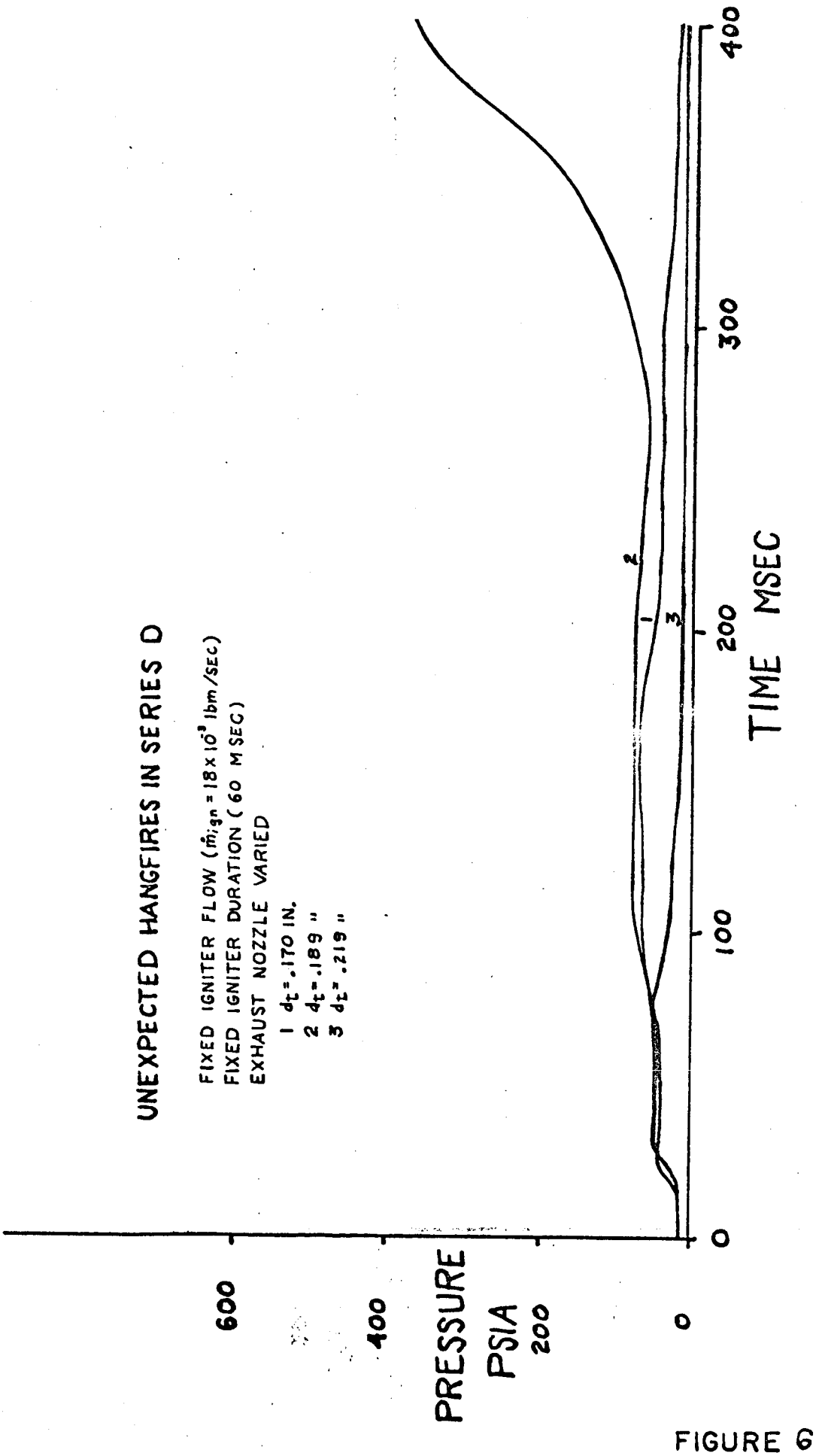
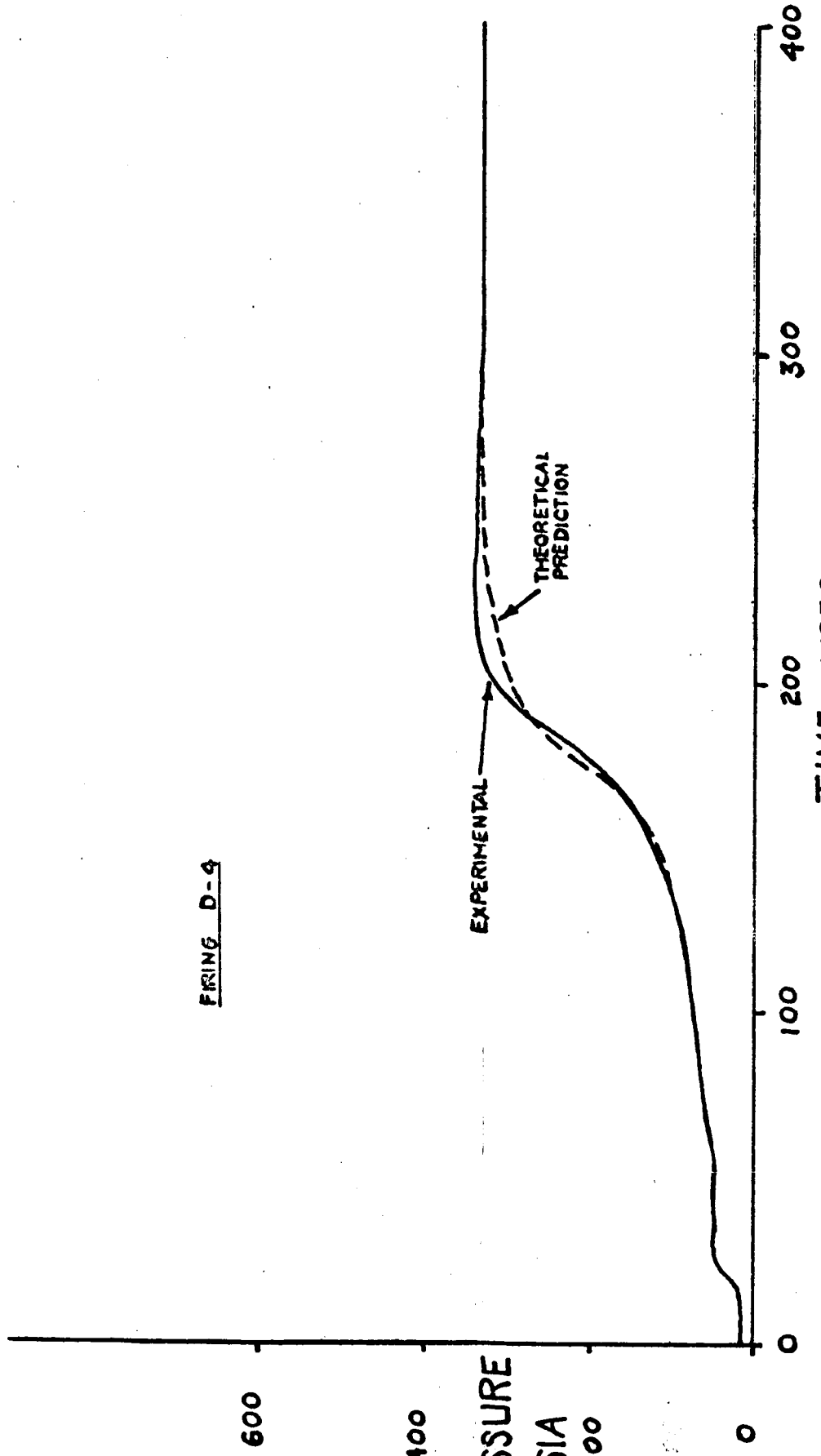


FIGURE 6

AP 26 R 4195 68



AP 26 R 4194 68

FIGURE 7

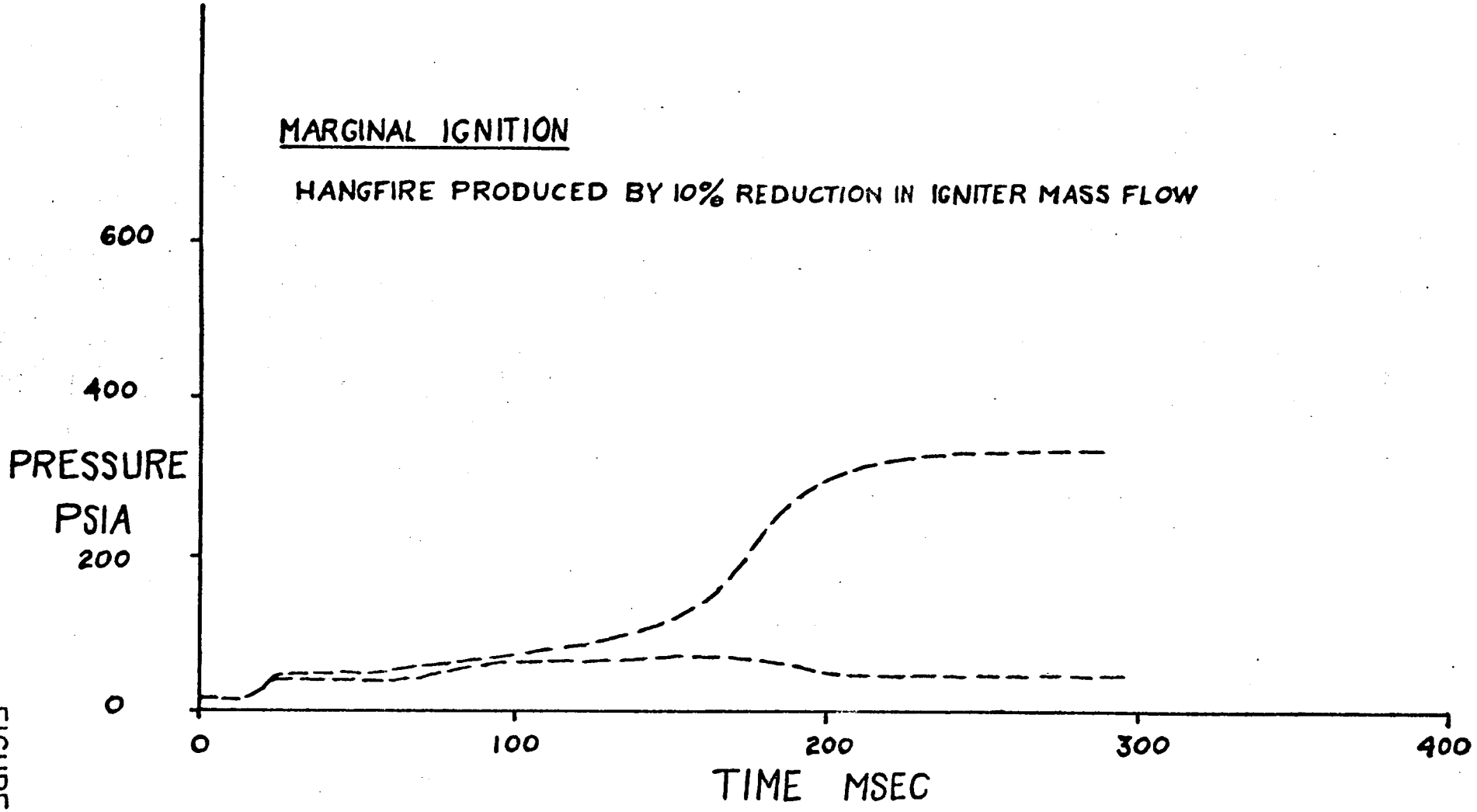

MARGINAL IGNITION
HANGFIRE PRODUCED BY 10% REDUCTION IN IGNITER MASS FLOW
600
400
200
0
PRESSURE
PSIA
0
100
200
300
400
TIME MSEC

FIGURE 8

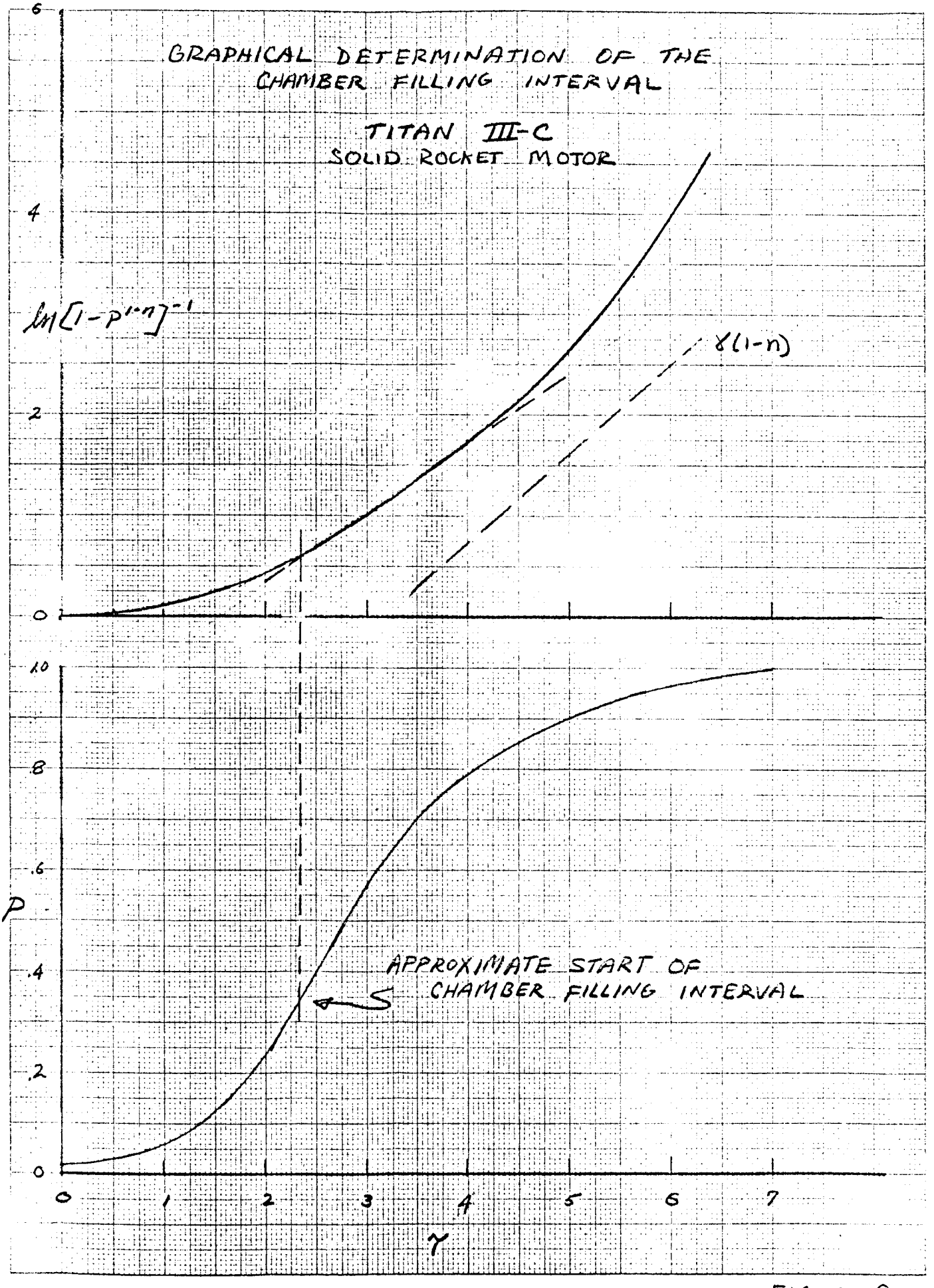
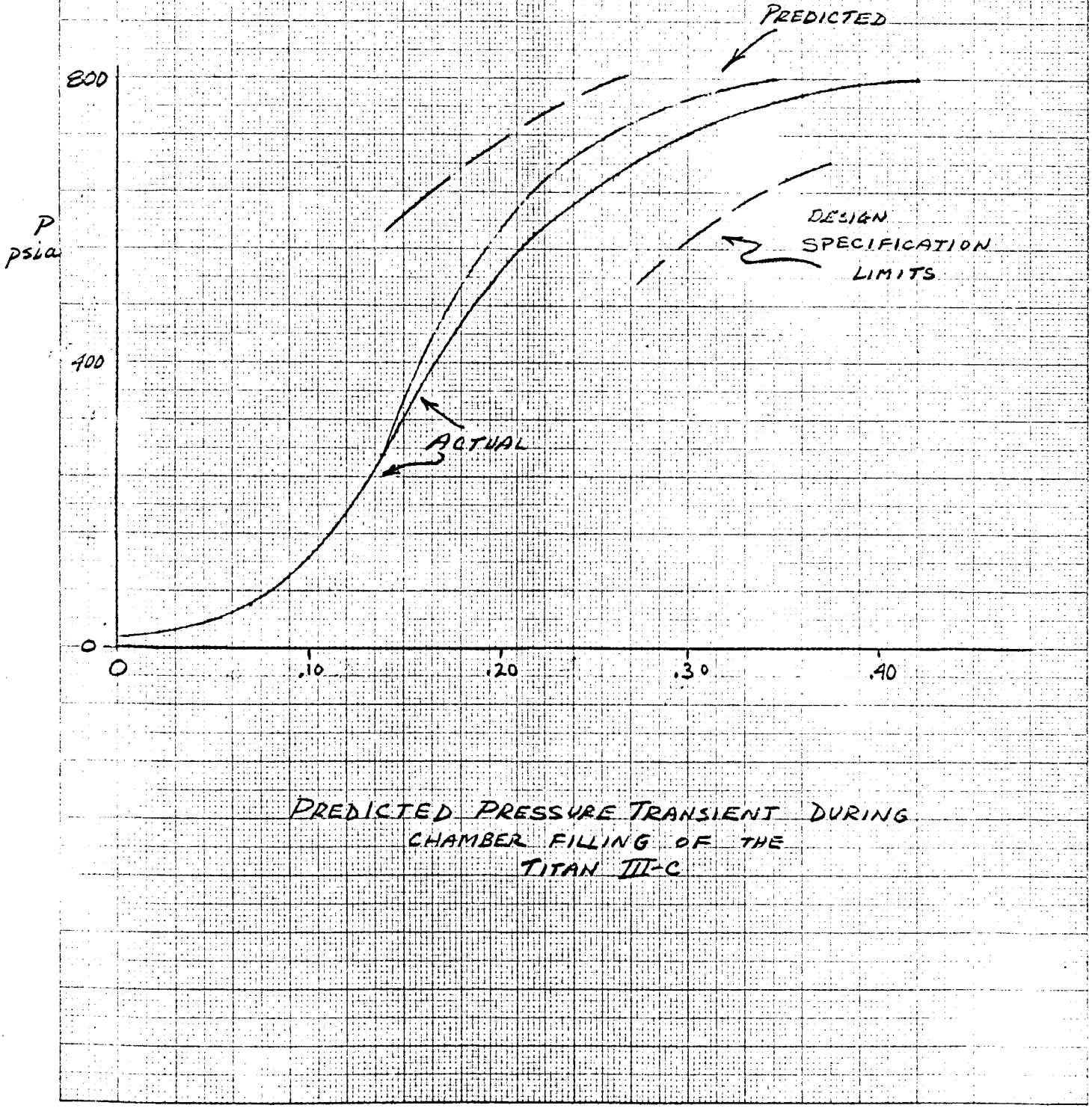

GRAPHICAL DETERMINATION OF THE CHAMBER FILLING INTERVAL
TITAN III-C
SOLID ROCKET MOTOR
$\ln[1-P^{1-n}]^{-1}$
$\gamma(1-n)$
P
APPROXIMATE START OF CHAMBER FILLING INTERVAL
γ
0
2
4
6
.2
.4
.6
.8
1.0
1
3
5
7

FIGURE 9



PREDICTED PRESSURE TRANSIENT DURING CHAMBER FILLING OF THE TITAN III-C

FIGURE 10

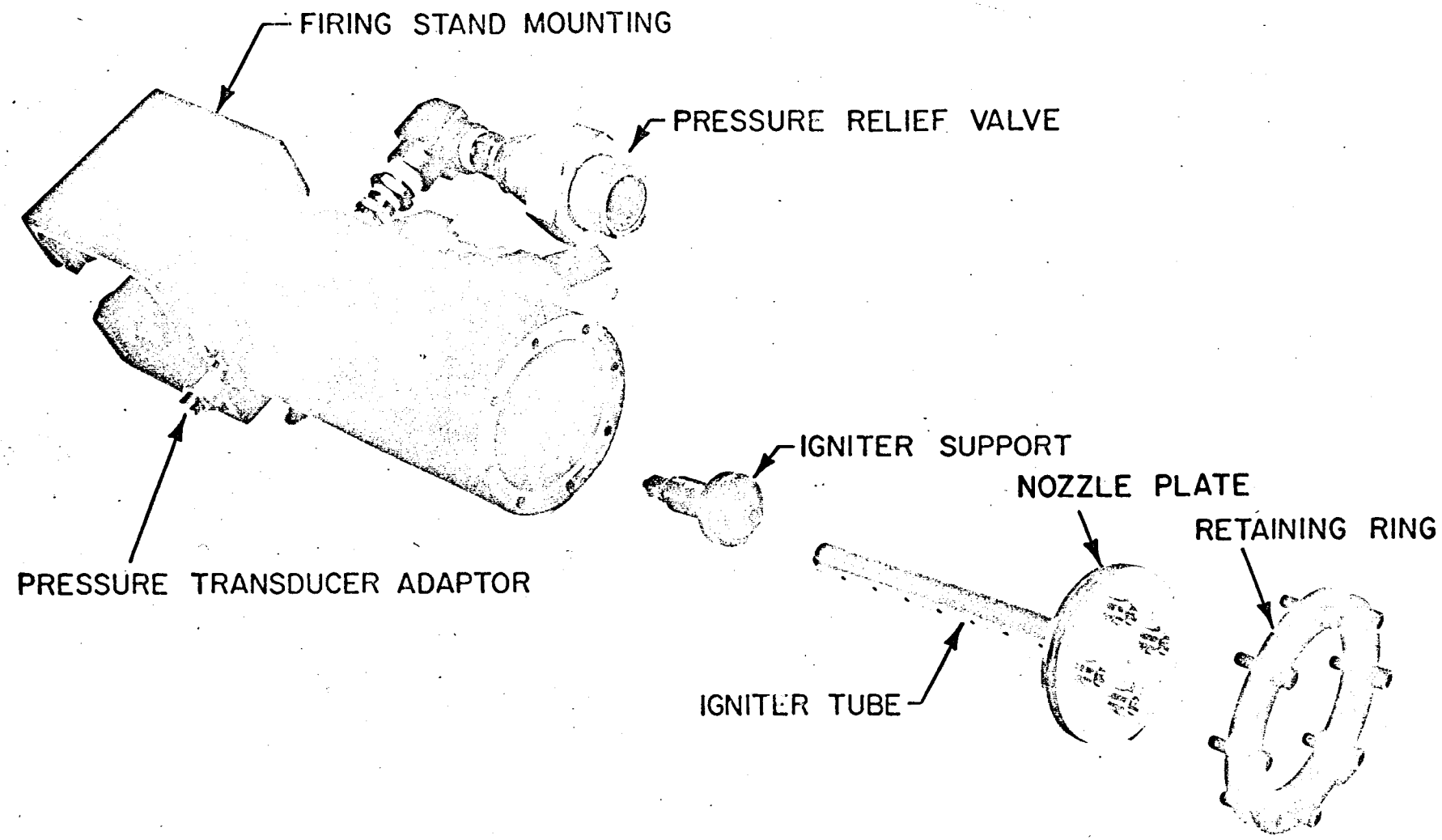


FIG. 11 EXPLODED VIEW OF FRANKFORD ARSENAL COMBUSTOR

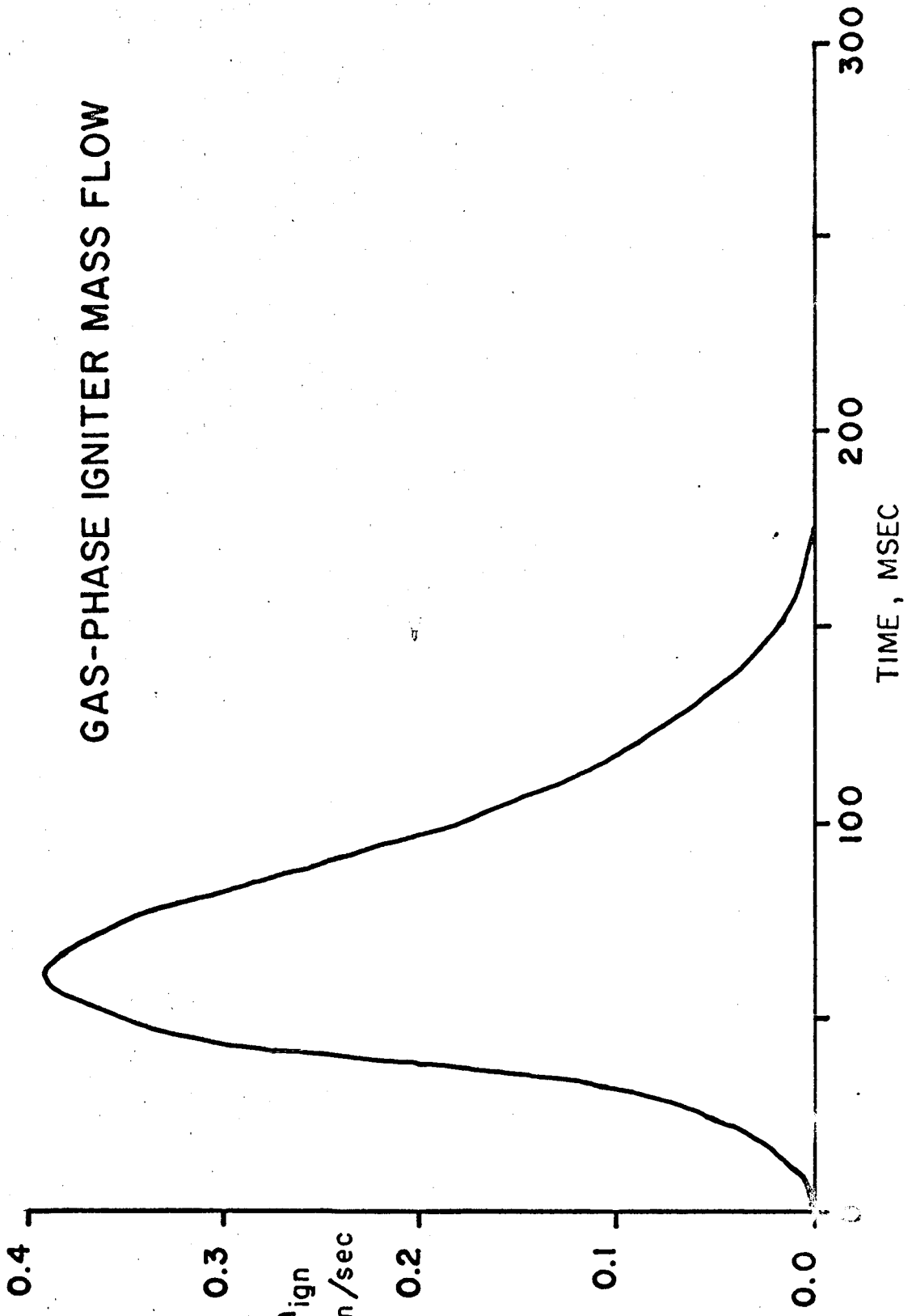

GAS-PHASE IGNITER MASS FLOW
0.4
0.3
0.2
0.1
0.0
$\dot{m}_{ign}$ lbm/sec
100
200
300
TIME, MSEC

FIGURE 12

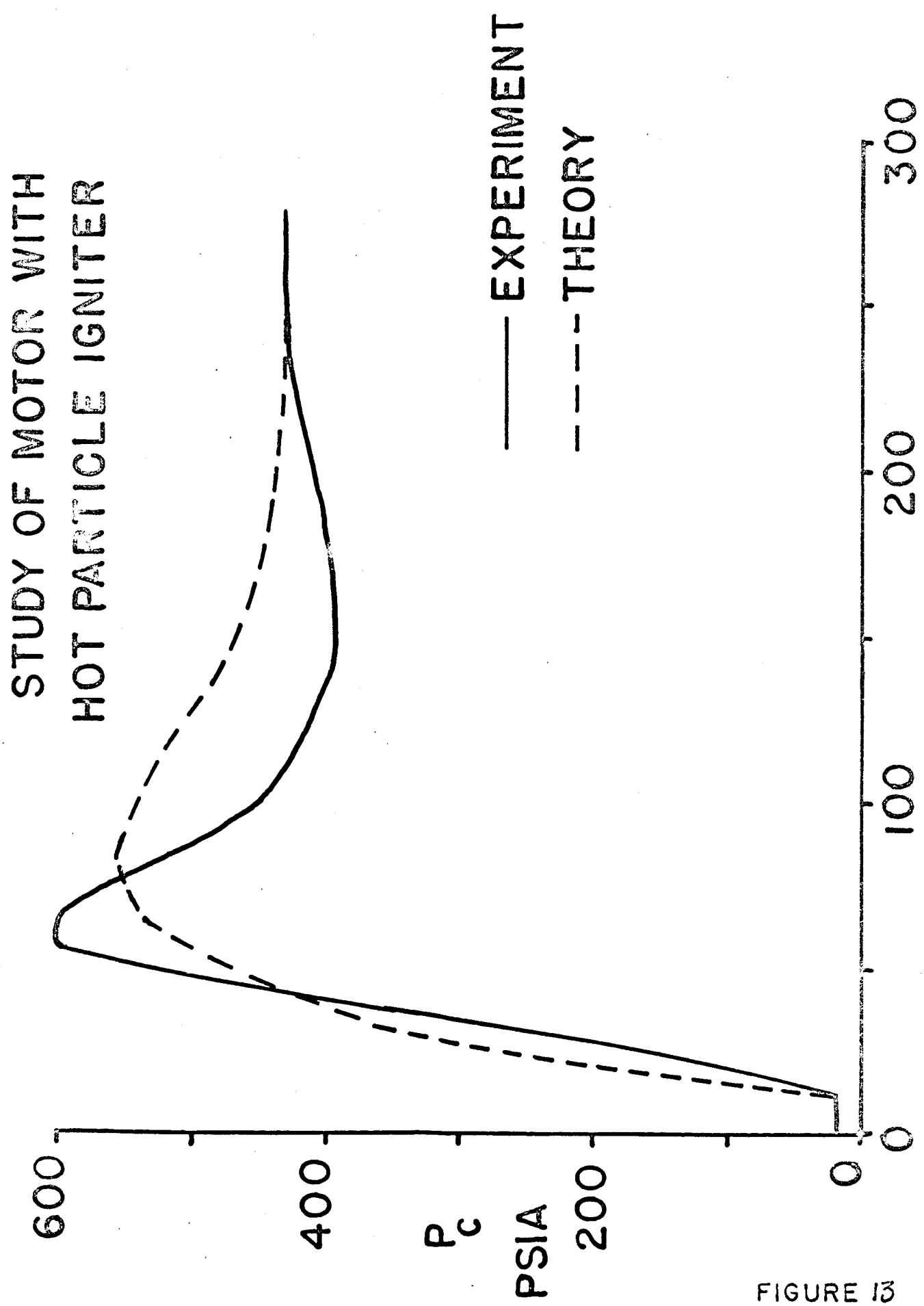

STUDY OF MOTOR WITH
HOT PARTICLE IGNITER
EXPERIMENT
THEORY
600
400
200
0
P_c
PSIA
0
100
200
300
TIME, MSEC

FIGURE 13

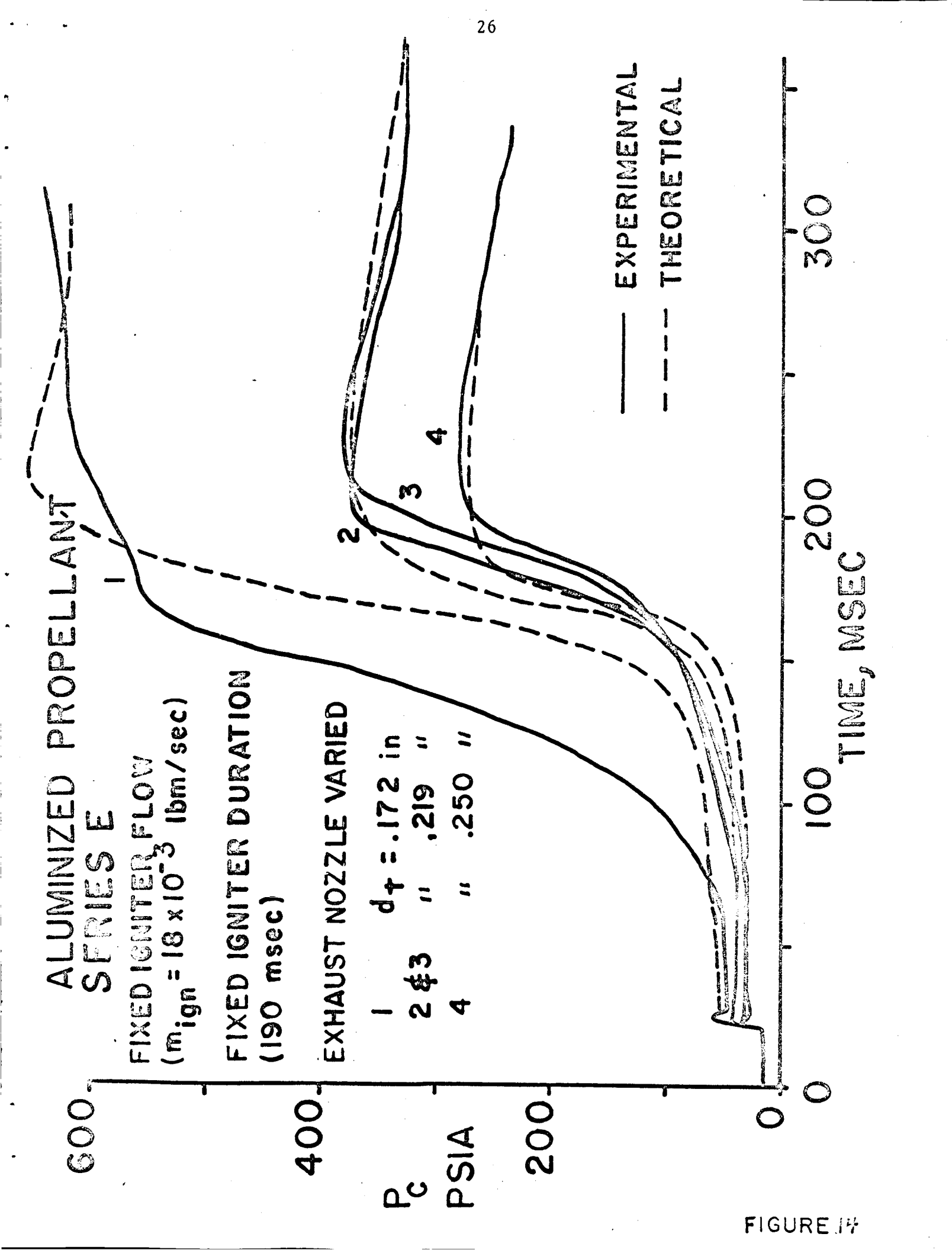
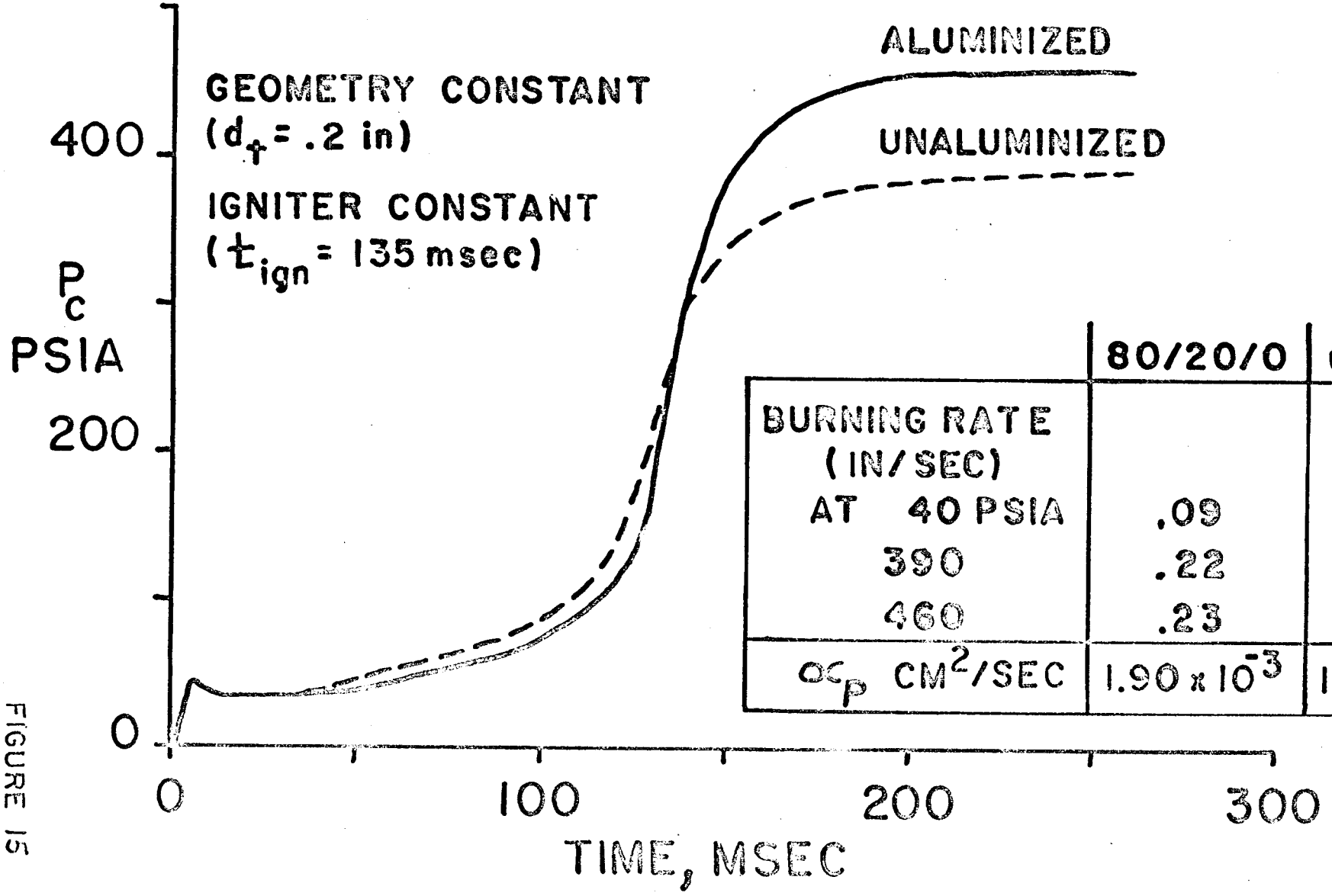

ALUMINIZED PROPELLANT
SERIES E
FIXED IGNITER FLOW
(m_{ign} = 18 x 10^{-3} lbm/sec)
FIXED IGNITER DURATION
(190 msec)
EXHAUST NOZZLE VARIED
1 d_t = .172 in
2 & 3 " .219 "
4 " .250 "
EXPERIMENTAL
THEORETICAL
P_c PSIA
600
400
200
0
0
100
200
300
TIME, MSEC
1
2
3
4

FIGURE 14

THEORETICAL PREDICTIONS FOR ALUMINIZED AND UNALUMINIZED PROPELLANT



	80/20/0	68/17/15
BURNING RATE (IN/SEC) AT 40 PSIA	.09	.12
390	.22	.21
460	.23	.22
αc_p CM^2/SEC	1.90×10^{-3}	1.93×10^{-3}

FIGURE 15

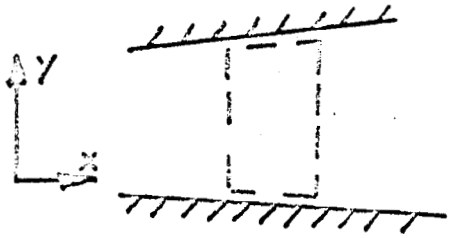
APPENDIX A

IGNITION TRANSIENT GAS DYNAMIC MODEL FOR ROCKET MOTORS WITH SMALL PORT-TO-THROAT AREA RATIOS

by

Kenneth K. Kuo*

In order to remove the restrictive assumptions of the present theoretical analysis, and thus more accurately model a wider class of rocket motors, a more sophisticated analysis has been started. The object of this work is to improve significantly the gas dynamic model by retaining the pressure and temperature gradients in the axial direction, by retaining the kinetic energy of the gases and by considering the designed variation in port cross section. As an illustration, a brief development of the new set of conservation equations is given here. The control volume shown below is considered.



The flow within the control volume is assumed to be one-dimensional. The reaction zone is again considered to be very thin compared to the control volume dimensions. This insures a reaction free control volume. The assumptions from the present analysis which are relaxed are listed as follows.

1. The axial pressure gradient generated by the combined effect of chemical reaction, heat convection and conduction laterally out of the control volume, the designed variation in flow cross section and mass addition is considered.

2. The axial temperature gradient is assumed to be significant. Detailed knowledge of the spatial distribution of the gas temperature will help in the heat transfer correlation work.

3. The designed variation in port cross section may greatly alter the flow conditions during the ignition transient and therefore should be taken into consideration.

The conservation equations are shown below.

Continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} - \frac{\rho_p \dot{r}_b}{r_p} + \rho u \frac{\partial \ln A_p}{\partial x} + \rho \frac{\partial \ln A_p}{\partial t} = 0$$

---

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Momentum

$$-\frac{\partial p}{\partial x} = \frac{\rho_p V_b b u}{A_p} + \rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x}$$

Energy

$$\rho\left(\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x}\right) - \left(\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x}\right) + \frac{\partial q_x}{\partial x}$$

$$= \left\{\rho_p V_b\left[(h_0 - h) + \frac{1}{2}u^2\right] - q_{loss}\right\}\frac{b}{A_p}$$

$$+ \left\{-p\frac{\partial \ln A_p}{\partial t} - q_x\frac{\partial \ln A_p}{\partial x}\right\}$$

In most cases the amount of propellant consumed during the ignition transient is small compared to the total mass stored in the rocket motor. This allows us to ignore the change of port area with respect to time. Furthermore, the heat conduction in the axial direction in the gas is small compared to the heat transfer in the lateral direction and thus can be ignored. For the present analysis viscous terms are neglected. These assumptions and the recombining of the conservation equations results in three coupled first order nonlinear partial differential equations.

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + RT\frac{\partial \ln p}{\partial x} + \frac{\rho_p V_b b u RT}{A_p p} = 0$$

$$\frac{\partial \ln T}{\partial t} + u\frac{\partial \ln T}{\partial x} + \frac{\gamma R}{c_p}\frac{\partial u}{\partial x} + \frac{\gamma R u}{c_p}\frac{\partial \ln A_p}{\partial x}$$

$$= \frac{\gamma R \rho_p V_b b}{A_p p}\left\{T_f - \frac{T}{\gamma} + \frac{u^2}{2}\right\} - \frac{q_{loss} b \gamma R}{p A_p c_p}$$

$$\frac{\partial \ln p}{\partial t} + u\frac{\partial \ln p}{\partial x} + \gamma\frac{\partial u}{\partial x} + \gamma u\frac{\partial \ln A_p}{\partial x}$$

$$= \frac{\gamma R \rho_p V_b b}{A_p p}\left[T_f + \frac{1}{2}u^2\right] - \frac{q_{loss} b \gamma R}{p A_p c_p}$$

These equations describe each of the elemental control volumes within the free volume of the rocket chamber. The equations of the present model are global equations for the entire rocket chamber.

In general, motors with small port-to-throat area ratios will experience higher rates of pressurization than motors with large port-to-throat area ratios. This is because the former class of motors have smaller L*'s than the latter and hence have shorter characteristic times. Thus, it is more important than it was in the previous analysis to couple these gas dynamic equations with a nonsteady burning rate equation. This nonsteady burning rate equation can be written in implicit form as $r(x,t) = r_{ss}(p(x))\,F(p(x,t))$. An erosive burning rate equation would also be needed to properly model motors with high volumetric loadings. Combining an erosive burning rate equation with the above nonsteady burning rate equation results in an equation of the form

$$r(x,t) = r_{ss}(p(x))\,F(p(x,t))\left[1 + k\,u(x,t)\right].$$

The new equations offer a formidable but not insurmountable mathematical problem. They are the only path available which will lead to any substantial improvement in the understanding of the gas dynamics involved in the ignition transient.

APPENDIX B

IGNITION TRANSIENT COMPUTER PREDICTION PROGRAM

Introduction: The System to be Solved The prupose of this computer program is to solve the system of equations which describe the entire ignition transient in a solid propellant rocket motor. The gas dynamics of the combustion chamber are written in non-dimensional form.

$$\frac{dp}{d\tau} = \gamma\left[S\frac{r_{bs}}{r_{eq}} + pT^{1/2} + T_{igp}\frac{\dot{m}_{igp}}{\dot{m}_{eq}}\right] \qquad \text{A-1}$$

$$\frac{dT}{d\tau} = \frac{T}{p}\left[(\gamma - T)S\frac{r_{bs}}{r_{eq}} - (\gamma-1)pT^{1/2} + \frac{\dot{m}_{igp}}{\dot{m}_{eq}}(\gamma T_{igp} - T)\right] \qquad \text{A-2}$$

These two equations represent the conservation of mass and energy in the control volume. The momentum equation has been uncoupled and the energy equation integrated under the assumptions of $\nabla p = o$, $\nabla T = o$ and $h \gg \frac{u^2}{2}$.

continued on next page

The mass flow into the system from the igniter, $\dot{m}_{ign}$, and the average temperature of the igniter gas in the control volume, T_{ign}, are assumed to be known input data.

Throughout the major portion of this particular study, the rates of pressurization considered were such that the propellant burning rate could be taken as the steady state value obtained from strand burner experiments. The burning rates of the propellants considered in this study could be adequately described by a curve fit of the strand burner data of the form $r_{ss} = k P_c^n$. This allows the Equation A-1 and A-2 to be rewritten in the form

$$\frac{dp}{dt} = \gamma \left[S k p^n - p T^{1/2} + T_{ign} \frac{\dot{m}_{ign}}{\dot{m}_{eq}} \right] \qquad \text{A-3}$$

$$\frac{dT}{dt} = \frac{T}{p} \left[(\gamma - T) S k p^n - (\gamma - 1) p T^{1/2} + \frac{\dot{m}_{ign}}{\dot{m}_{eq}} (\gamma T_{ign} - T) \right] \qquad \text{A-4}$$

There are a number of situations in which this treatment of the burning rate is not adequate. First, the burning rate of many propellants cannot be fitted over the entire pressure range of interest by a simple $r_{ss} = k P_c^n$ equation. Figure 17 is an example of such a propellant. The second notable exception is the case of high rates of pressurization where the burning rate is now a function of p and dp/dt. In these two cases Equations A-1 and A-2 must be solved directly with the burning rate supplied by a subroutine. Such flexibility has been developed in the computer program so that a burning rate of any given form can be used.

In order to calculate the instantaneous area burning, S, appearing in either set of equations, three elements are necessary: First, the heat flux

to the solid must be calculated; second, the heat diffusion equation in the solid must be solved for the surface temperature of each propellant element; and third, the critical surface ignition temperature for the particular propellant must be supplied as input data.

In this study, the heat flux to the solid surface was assumed to take two forms. First, and dominant in most situations, is convection from the gas phase. An empirical correlation for the convection was used:

$$Nu_{x+a} = .0734\, Re_{x+a}^{0.8}$$

The second energy source is the heat release by the propellant below the critical ignition temperature (self-heating). Although physically this must be a distributed energy source, it is assumed to be concentrated at the surface. This allows this term to be placed in the boundary condition of the solid phase heat diffusion equation. Thus, the surface temperature to be written as:

$$T_s = T_o + \frac{1}{\lambda_p}\sqrt{\frac{\alpha_p}{\pi}}\int_0^t \frac{\dot{q}_{gas} + \dot{q}_{surf}}{\sqrt{t-\tau}}\, d\tau \qquad \text{A-5}$$

The gas phase convection heat flux is written as

$$\dot{q}_{gas} = h_{conv}\,\Delta T = .0734\,\frac{\lambda_g \Delta T}{(x+a)}\, Re_{x+a}^{0.8}$$

$$= .0734\,\frac{\lambda_g \Delta T}{(x+a)}\left\{\frac{\rho_{eq} A_t L}{c^* A_p \mu_g}\left(\frac{a}{L}+\frac{x}{L}\right)\left[\frac{P}{T^{1/2}} + \left(1-\frac{x}{L}\right)\frac{d(P/T)}{d\tau}\right]\right\}^{0.8} \qquad \text{A-6}$$

The term in brackets is the mass flow over station X, corrected for the mass storage in the portion of the control volume upstream of station X. ΔT is the driving potential across the boundary layer. This was taken to be constant in time and space.

The self-heating term is taken as

$$\dot{q}_{sur} = \rho_p Q A_s e^{-E_s/RT_s} \qquad \text{A-7}$$

Equations A-6 and A-7 are substituted into Equation A-5 to obtain the final form of the solution for T_s.

$$T_s = T_o + \frac{1}{\lambda_p}\sqrt{\frac{\kappa_p}{\pi}}\int_0^t \left[.0734 \frac{\lambda_g \Delta T}{(x+a)} \left\{ \frac{\rho_{ig} A_n L}{c^* A_p \mu_g} \left(\frac{a}{L} + \frac{x}{L}\right)\left[\frac{\rho}{T^{1/2}} + \left(1-\frac{x}{L}\right)\frac{d(\rho/T^{1/2})}{d\tau}\right]_0 \right\} + \rho_p Q A_s e^{-E_s/RT_s} \right] \frac{d\tau}{\sqrt{t-\tau}} \qquad \text{A-8}$$

This is a nonlinear integral equation due to the appearance of T_s in the self-heating term.

The initial and boundary conditions on Equations A-1, A-2 (or alternatively A-3 and A-4) and A-8 are

$$T(o) = T_{ambient}$$

$$P(o) = P_{ambient}$$

$$S(o) = 0$$

$$T_p(x,y,o) = T_o$$

$$T_p(x,\infty,t) = T_o$$

$$\left(\lambda_p \frac{\partial T}{\partial y}\right)_{y=o} = -\left[\dot{q}_{gas}(x,t) + \dot{q}_{sur}(x,t)\right] .$$

In summary then, the system of equations to be solved consists of two first order, nonlinear coupled ordinary differential equations for P(t) and $\bar{T}(t)$ and a nonlinear integro-differential equation for $T_s(x,t)$. The integro-differential equation for $T_s(x,t)$ is coupled to the equations for p and T through the calculation of the mass flux. ΔT, T_{IG}, $\dot{m}_{ign}$ and T_{ign} are considered as input data. The burning rate, r, after ignition has been achieved can be handled in several ways, as outlined above.

This system of equations can be solved analytically only under very restrictive assumptions. For example, if $S=1$, $\dot{m}_{ign}=0$ and $T(t)$ constant, the equation for P is a Bernoulli equation which can be linearized and solved analytically for P(t). However, in the majority of interesting cases such simplifications are not possible and recourse to digital computer solution is necessary.

Numerical Methods The differential equation for p and T are solved with a two point Predictor-Corrector technique. The first point is given by the specified initial conditions. The second point is obtained by a modified Runge-Kutta method. Given these two points, the Predictor predicts the next point and the corrector corrects the value to within a specified tolerance. Once this system is started, the technique propagates itself, always using the previous two points to first predict and then to correct the next point.

The Predictor: $$\rho^{o}_{M+1} = \rho_{M-1} + 2\Delta t \frac{d\rho(\rho_M, T_M)}{dt} \qquad \text{A-9}$$

The Corrector: $$\rho^{i}_{M+1} = \rho_M + \frac{\Delta t}{2}\left[\frac{d\rho(\rho_M, T_M)}{dt} + \frac{d\rho(\rho^{i-1}_{M+1}, T^{i-1}_{M+1})}{dt}\right] \qquad \text{A-10}$$

The superscript i represents the ith iteration through the Corrector equation, and the subscript M represents the number of time-steps taken up to that point. There are simultaneous equations for T. These equations are developed and discussed in Reference A-1.

The geometric interpretation of these equations is shown in Figures A-1 and A-2. The Predictor consists of drawing a straight line through the point (M-1) by using the value of the slope at M. The predicted value is then the intersection of this line with the line t = M+1. The Corrector calculates the point (M+1) by averaging the slopes at points (M)

and (M+1). The slope at point (M+1) is iterated until the values of pressure and temperature have converged to the specified tolerance.

$$\left| p_{M+1}^{i} - p_{M+1}^{i-1} \right| , \left| T_{M+1}^{i} - T_{M+1}^{i-1} \right| < \epsilon \qquad \text{A-11}$$

The tolerance, ϵ, was taken in this study to be 10^{-5} and $\Delta\tau$ was taken as .03. This combination resulted in satisfying Equation A-11 in something near the recommended optimum number of two iterations per step.

Using the concept of successive ignitions, the propellant grain, is broken up into a number of segments, and $T_s(t)$ (Equation A-8) of each element is calculated separately. Generally, one hundred segments were considered, but the first segment (the leading edge of the propellant grain) was broken into an additional ten subsegments in order to predict first ignition more accurately. The surface temperature integral equation (A-8) is evaluated using a simple trapezoidal rule, shown in Figure A-3. In the calculation of Q(M), T_s was taken as the surface temperature one Δt earlier than the time being considered. In most cases, the difference between the two temperatures is a fraction of a degree, and when placed in the negative exponential self-heating term is negligible when the surface temperature is below 90% of the critical ignition temperature. However, when the surface temperature approaches the critical value, the effect of the difference can become significant. When this occurs, it is necessary to iterate T_s until the values converge.

The Computer Program For convenience, the program is divided into a main program and five essential subroutines. Actually there are two distinct programs - one which uses Equations A-1 and A-2 and a special burning rate subroutine calculation and a second program which uses Equations

A-3 and A-4 and $r_{ss} = \kappa P_c^n$. These programs are designated PPSPIG2 (for Pressure Prediction of Solid Propellant Ignition) and PPSPIG-1 respectively. There is, of course, a great deal of similarity between these two programs.

Copies of the two programs are given on pages B-16 and B-40. The flow diagram is given in Figure A-4. The programs were set-up so as to be completely self-contained. The first pages contain a complete table of nomenclature. Liberal use of comment cards throughout the program supply guides to the computer logic. This instructional format is supplemented below by a brief introduction as to the purpose of each section of the program. The input-output formats are detailed on page B-8.

The Main Program serves to coordinate the calculations of the various subroutines and to handle input and output. The incrementing of time and grain position is performed here, as well as some decision making, i.e., whether flame spreading has ended, whether the transient has ended, etc.

Subroutine NXTPNT (Next Pressure and Temperature) integrates the differential equations using the second order Predictor-Corrector method outlined above.

Subroutine WARUM calculates the surface temperature of the particular grain element under consideration. This amounts to evaluation of Equation A-8. Most of the execution time of the program is spent in this subroutine. A great deal of effort was expended to make these computations as efficient as possible.

Subroutine FLOIG calculates the mass flow from the igniter at the current time and it evaluates the terms in the differential equations which are related to igniter effects. Essentially, this is the subroutine which contains the characterization of the igniter.

ten columns. The nozzle diameter in inches is put in the second ten columns.

Fifth Card: The following information is placed in consecutive groups of ten columns: 1. steady state igniter flow duration in seconds, 2. a time value in seconds during the igniter quadratic decay, 3. the time in seconds at which the igniter mass flow is zero, 4. the steady state igniter flow rate in lbs/sec, 5. the igniter mass flow rate in lbs/sec corresponding to the time in item 2, 6. the igniter mass flow rate at the end of igniter operation, 7. the time in seconds at which the ignition nozzle unchokes.

Sixth Card: The following information is placed in consecutive groups of ten columns: 1. igniter throat diameter in inches, 2. igniter chamber volume in cm^3, 3. igniter gas thermal conductivity in cal/cm sec ^{o}c, 4. igniter gas viscosity in g/cm sec.

Seventh Card: The following information is placed in consecutive groups of ten columns: 1. width or circumference of propellant grain in , 2. main chamber volume in cm^3, 3. port area in cm^2, 4. propellant leading edge in

Eighth Card: The following information is placed in consecutive groups of ten columns: 1. ratio of specific heats, 2. propellant ignition temperature in ^{o}C, 3. propellant density in g/cm^3, 4. self-heating pre-exponential in cm/sec, 5. activation energy in cal, 6. surface heat release parameter in cal/g, 7. initial propellant temperature in ^{o}C, 8. propellant adiabatic flame temperature ^{o}K.

Ninth Card: The following information is placed in consecutive groups of ten columns: 1. heat transfer correlation coefficient, 2. heat transfer correlation exponent, 3. propellant thermal conductivity in cal/cm sec^{o}C,

4. thermal conductivity of propellant combustion products in cal/cm sec ^{o}C, 5. propellant thermal diffusivity in cm^2/sec, 6. viscosity of propellant combustion products in g/cm sec, 7. burning rate exponent, 8. burning rate coefficient.

Tenth Card: The following information is placed in consecutive groups of ten columns: 1. non-dimensional time step size (0.03t* is recommended), 2. convergence tolerance for the differential equations (10^{-5} is recommended), 3. initial chamber pressure in psia, 4. temperature of igniter gases in main chamber in ^{o}K, 5. initial area ignited (usually zero), 6. average temperature difference between the chamber gases and the propellant surface for the convective heat flux calculation.

The data for the second run would begin with the Second Card and continue through the Tenth Card.

Additional Input for PPSPIG2

In order to use the program which has been adapted to handle *non*-kP_c^n burning rate expressions, the following addition input is needed: After the fifth card, a card is put in with the number of burning rate-pressure pairs that are to be read in. This information should be right adjusted in the first ten columns. Following this the specified number of pairs are read in, one pair per card. The pressure in psia is placed in the first ten columns, and the burning rate in inches per second in the second ten columns. The rest of the data input cards remain the same except for the ninth card. On this card the position allotted to the burning rate exponent and coefficient should be left blank.

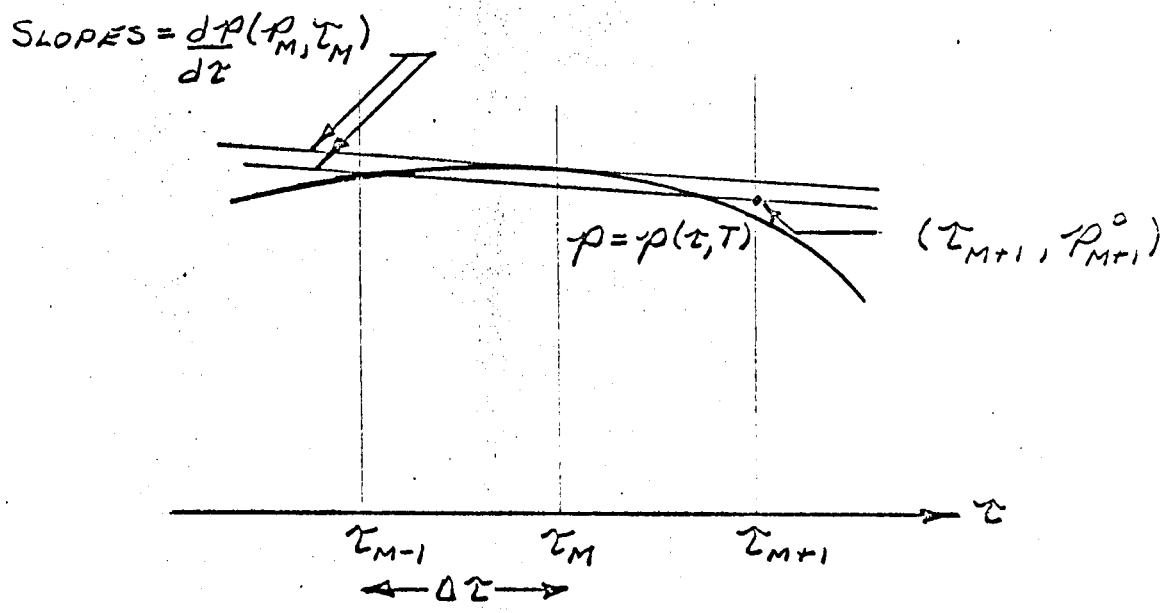

FIGURE A-1

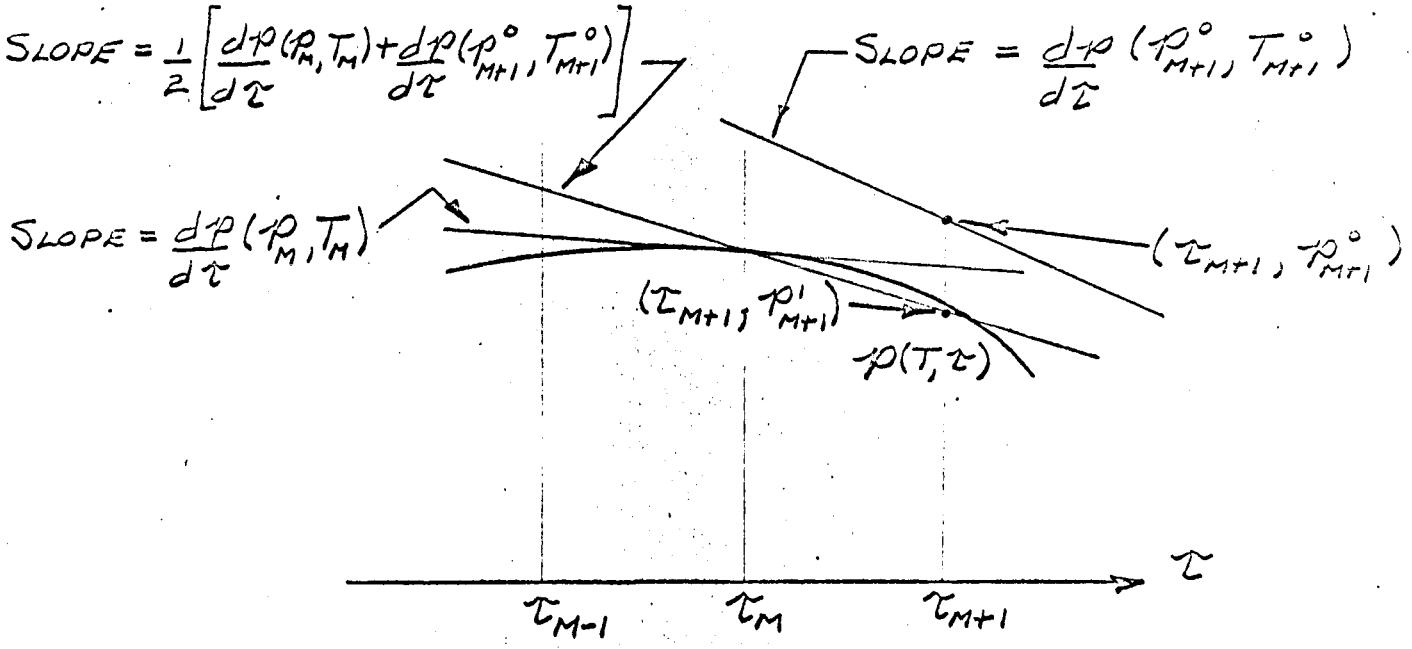

FIGURE A-2

$$\int_0^t \frac{Q(t')}{(t-t')^{1/2}}\,dt' = \frac{Q(0)}{t^{1/2}} + \sum_{n=1}^{N-1} \frac{1}{2}\left[\frac{Q(n-1)}{(t-t'+\Delta t)^{1/2}} + \frac{Q(n)}{(t-t')^{1/2}}\right]\Delta t'$$

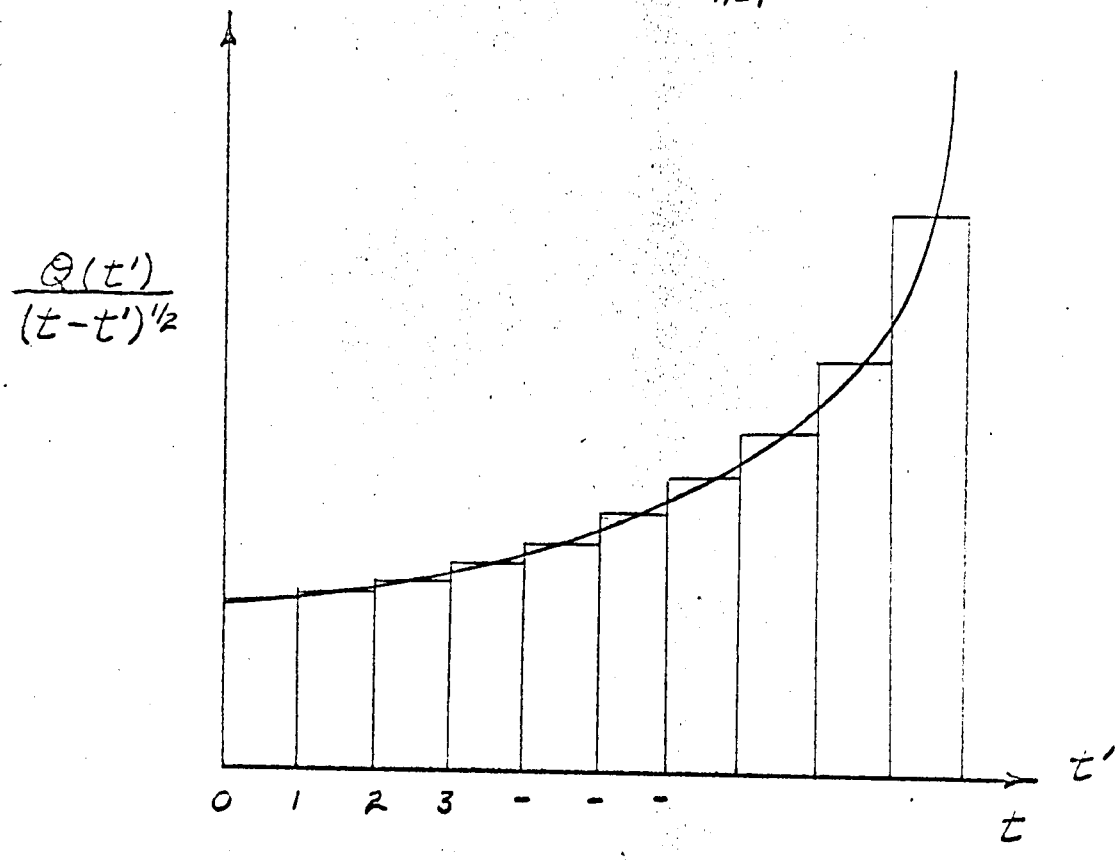

FIGURE A-3

COMPUTER PROGRAM FLOW CHART

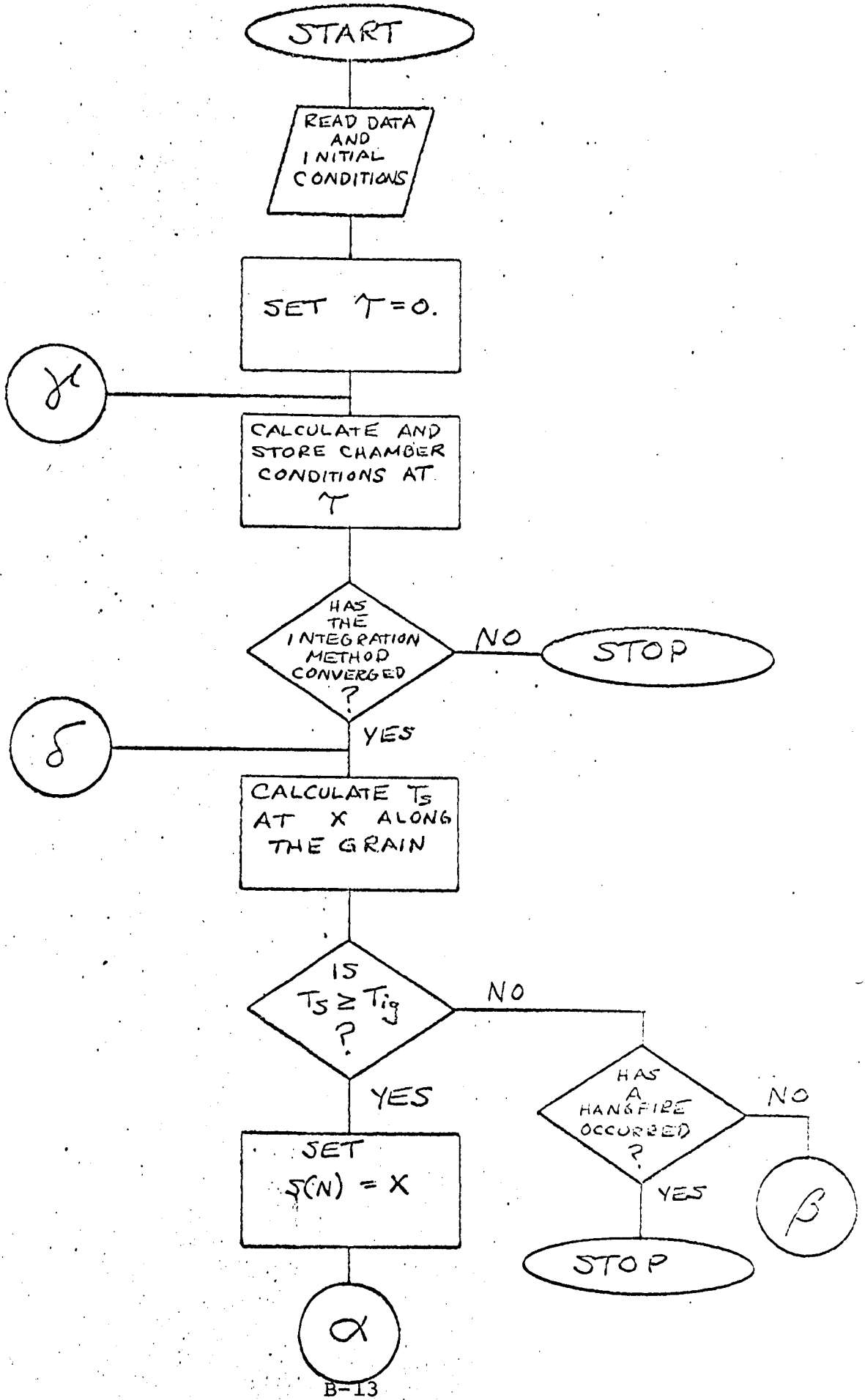

FIGURE A-4

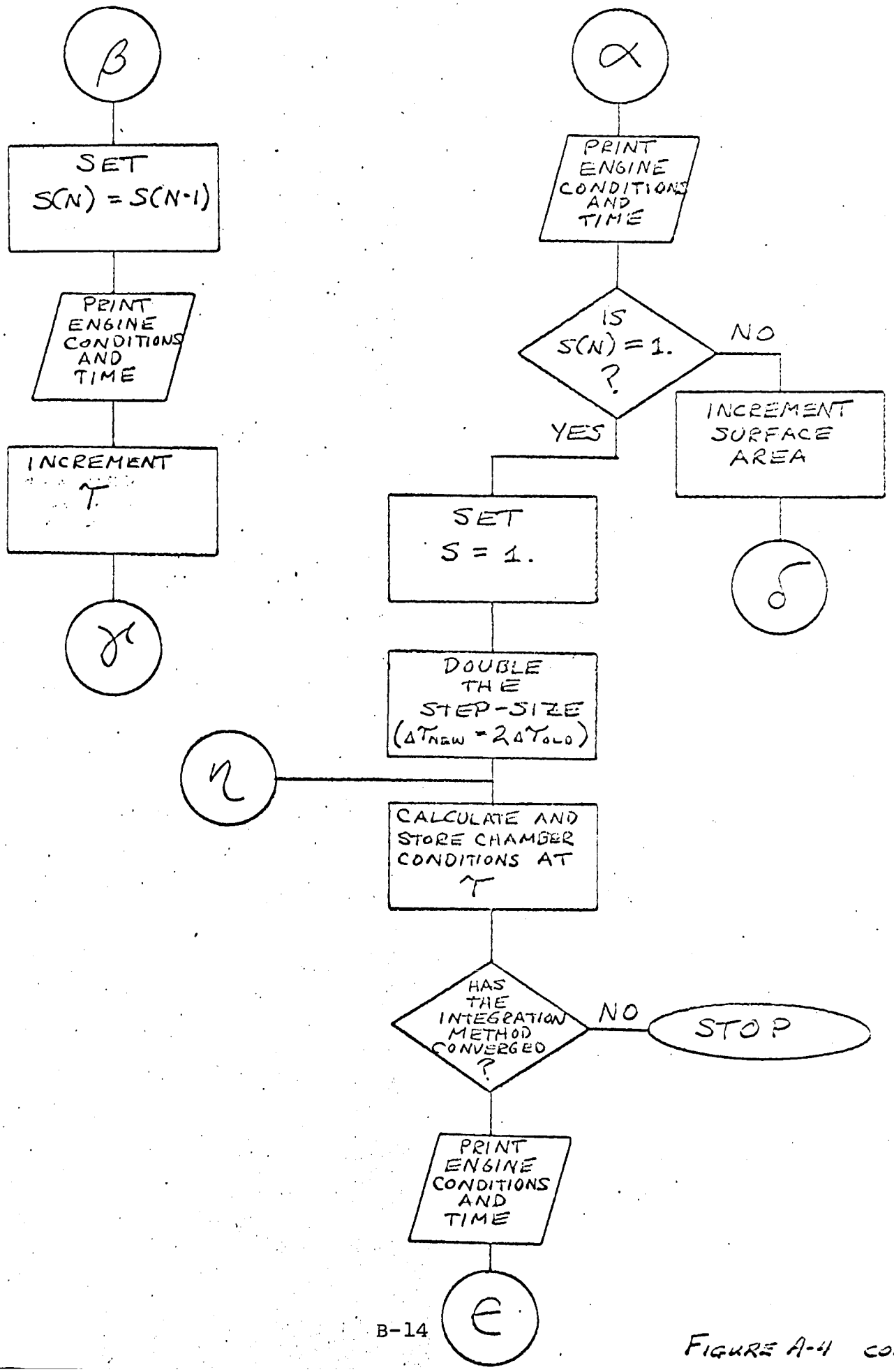

FIGURE A-4 CONTD.

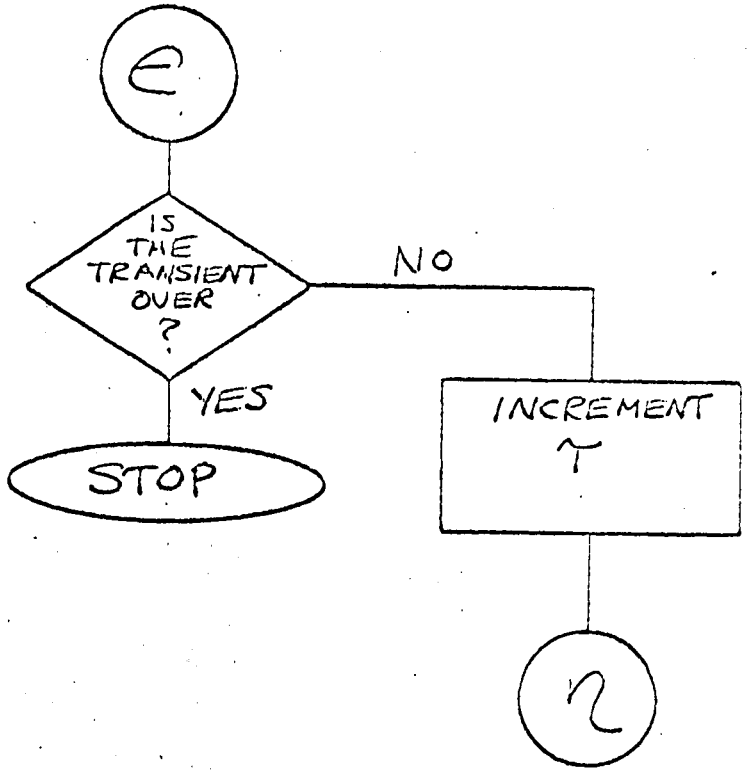

FIGURE A-4 CONTD.

```
C
C
C                                   COMMENTS
C
C
C
C
C
C
C
C
C
C
C
C     PROGRAM NAME ---- PPSPIG1, FOR PRESSURE PREDICTION OF
C     SOLID PROPELLANT IGNITION, PROGRAM #1.
C
C         THE FOLLOWING PEOPLE HAVE CONTRIBUTED TO THIS PROGRAM ---
C
C      KIM H. PARKER
C      WILLIAM J. MOST
C      GERALD F. DILAURO
C      LAWRENCE H. LINDEN
C      BRUCE W. MACDONALD
C
C
C
C
C                   NOMENCLATURE
C
C                         NOTE : NOT ALL OF THE NOMENCLATURE IN THIS
C                         LIST IS USED IN ANY GIVEN PROGRAM. SOME
C                         NOTATION REFERS TO ALTERNATIVE SUBROUTINES.
C
C
C
C
C
C     ***************************************************************************
C       A,B,C ARE CONSTANTS IN THE QUADRATIC EQUATION FOR THE IGNITER TAIL-
C     OFF IN SUBROUTINE "FLOIG".
C       ACONST = PCIG*ATIG/(DSQRT(TCIG)*AT)
C       ACROS IS THE PORT CROSS-SECTIONAL AREA OF THE MAIN CHAMBER (CM**2).
C       AL IS THE NON-DIMENSIONAL ALD.
C       ALD IS THE LENGTH OF THE BOUNDARY LAYER LEADING EDGE AHEAD OF THE
C     PROPELLANT LEADING EDGE (CM).
C       ALPHP IS THE THERMAL DIFFUSIVITY OF THE PROPELLANT (CM**2/SEC).
C       ALPLSX = AL + X
C       AN IS THE EXPONENT IN THE BURNING RATE LAW.
C       AS IS THE PRE-EXPONENTIAL IN BR = AS*EXP(E/(R*TS)) (CM/SEC).
C       AT IS THE EXHAUST NOZZLE AREA (CM**2).
C       ATIG IS THE IGNITER NOZZLE AREA (CM**2).
C       BR IS THE BURNING RATE (IN/SEC).
C       BCON = P(1)/DSQRT(TEMP(1)).
C       CONDUC IS THE MASS-WEIGHTED AVERAGE OF THE THERMAL CONDUCTIVITIES
C     OF THE IGNITER AND PROPELLANT GASES MULTIPLIED BY RXTX.
C       CONST = GAMMA*TCIG OR GAMMA*TIGNN IF THE NON-ADIABATICITY OF THE
C     IGNITER FLOW IS KNOWN.
C       CSTAR IS THE MOTOR CHARACTERISTIC VELOCITY IN FEET PER SECOND.
```

```
C     CSTARI IS THE IGNITER CHARACTERISTIC VELOCITY IN FEET PER SECOND.
C   IT CAN BE BASED ON TCIG OR TIGNN. THE CHOICE MUST BE SPECIFIED AND
C   USED ACCORDINGLY.
C     D IS THE TIME AT WHICH GIM = 0.0 (SEC).
C     DELREF = DELT*TREF (SECONDS).
C     DELT IS THE INCREMENT OF TAU -- USUALLY 0.03 UNITS.
C     DELX IS THE INCREMENT OF GRAIN LENGTH -- USUALLY 0.01.
C     DIFF IS A DUMMY TIME VARIABLE USED IN  SUBROUTINE "WARUM".
C     DPDT IS THE NON-DIMENSIONAL DERIVATIVE OF PRESSURE W.R.T. TIME.
C     DTDT IS THE NON-DIMENSIONAL DERIVATIVE OF TEMPERATURE W.R.T. TIME.
C     DT IS THE EXHAUST THROAT DIAMETER (IN).
C     DTIG IS THE IGNITER THROAT DIAMETER (IN).
C     E IS THE ACTIVATION ENERGY OF THE PROPELLANT (CAL/MOLE).
C     EOVERR IS THE ACTIVATION ENERGY E DIVIDED BY THE GAS CONSTANT R.
C     ETPRES,ETTEMP ARE THE TRUNCATION ERRORS IN CALCULATING 'P' AND 'T'
C   USING THE PREDICTOR-CORRECTOR METHOD.
C     FLEQ IS THE EQUILIBRIUM MASS-FLOW RATE (LBM/SEC).
C     FLOW IS THE IGNITER MASS FLOW RATE BEFORE THE QUADRATIC TAILOFF
C   IN LBM/SEC.
C     GAMMA IS THE RATIO OF SPECIFIC HEATS.
C     GAMSQ IS A FUNCTION OF GAMMA, = GAMMA*(2./(GAMMA-1.)**(GAMMA+1.)/
C   (GAMMA-1.)
C     GIM IS THE IGNITER MASS FLOW RATE AT ANY TIME (LBM/SEC).
C     GIMOFL IS THE NON-DIMENSIONAL IGNITER MASS FLOW RATE.
C   SUBROUTINE 'NXTPNT'.
C     JXYZ IS A VARIABLE WHICH ACTS AS A SIGNAL THAT TERMINATES EXECUTION
C   OF A RUN IF : 1) THERE IS A HANGFIRE, OR 2) THE INTEGRATION OF THE
C   DIFFERENTIAL EQUATIONS IS NOT CONVERGING.
C     KABANG ACTS AS A SIGNAL ON WHETHER OR NOT TO TEST FOR INCREASING
C   THE AREA STEP SIZE FROM 0.001 TO 0.01.
C     KOUNT KEEPS THE PROGRAM FROM GETTING 'HUNG UP' IN PERFORMING AN
C   INFINITE NUMBER OF TIME INCREMENTS.
C     LALL IS A TIME COUNTER.
C     NOS IS THE INTEGRAL NUMBER OF IGNITED SURFACE ELEMENTS.
C     NUX IS THE NUSSELT NUMBER AT A GIVEN POSITION X.
C     ONEMIX = 1. - X
C     P IS THE NON-DIMENSIONAL CHAMBER PRESSURE.
C     POTHAF = P(K)/DSQRT(TEMP(K)). THIS IS SIMPLY A CONSTANT USED IN
C   THE HEAT TRANSFER SUBROUTINE.
C     P9 IS THE DIMENSIONAL INITIAL PRESSURE.
C     PCIG IS THE NON-DIMENSIONAL PRESSURE IN THE IGNITER CHAMBER.
C     PEQ IS THE EQUILIBRIUM CHAMBER PRESSURE IN PSIA. IT CAN BE TAKEN
C   AS EITHER THE THEORETICAL OR EXPERIMENTAL VALUE.
C     PI = 3.1415926536
C     PMIG = TIGNN*GIM/FLEQ OR TCIG*GIM/FLEQ.
C     PN IS THE NON-DIMENSIONAL BURNING RATE, = P**AN.
C     PRINCE IS A TEST FOR THE CONVERGENCE OF THE INTEGRATION OF THE
C   DIFFERENTIAL EQUATIONS.
C     PRODEN IS THE PROPELLANT DENSITY IN GM/CM**3.
C     PY IS AN INTERMEDIATE NON-CONVERGED VALUE OF 'P'.
C     Q IS THE VOLUMETRIC HEAT RELEASE ASSIGNED TO THE SURFACE, IN CAL/GM.
C     Q1 IS THE TOTAL HEAT FLUX AT TAU = DEL, IN CAL/CM**2*SEC.
C     QM IS THE TOTAL HEAT FLUX AT TIME M, IN CAL/(CM**2*SEC).
C     QMCONV IS THE CONVECTIVE HEAT FLUX AT TIME M, IN CAL/(CM**2*SEC).
C     QPA IS THE PRE-EXPONENTIAL IN THE SURFACE HEAT RELEASE EQUATION,
C   = Q*PRODEN*AS.
```

```
C     QMSURF IS THE SURFACE HEAT RELEASE, IN CAL/(CM**2*SEC).
C     RENUK IS THE REYNOLD'S NUMBER COEFFICIENT.
C     RENUX IS THE REYNOLD'S NUMBER EXPONENT.
C     REX IS THE REYNOLD'S NUMBER AT GRAIN POSITION X.
C     REXEQ IS THE EQUILIBRIUM REYNOLD'S NUMBER,@ X = XL.
C   NUMBER.
C     REXOMU IS THE GAS VISCOSITY DIVIDED INTO THE EQUILIBRIUM REYNOLD'S
C     RHELP IS THE MASS STORAGE TERM IN REX, AND IS EQUAL TO THE
C   DERIVATIVE OF PRESSURE DIVIDED BY TEMPERATURE WITH RESPECT TO TIME.
C     RXTX = RENUK*TDIFE/XL.
C     S IS THE NON-DIMENSIONAL AREA ALREADY IGNITED.
C     S9 IS THE PER CENTAGE OF GRAIN SURFACE IGNITED.
C     SAMEAR ANSWERS THE QUESTION "IS THE AREA BURNING THE SAME AS LAST
C   TIME ?"
C     SAVEXX IS THE INITIAL PROPELLANT TEMPERATURE CONVERTED TO KELVIN.
C     SCON = RENUK*XLAMG*(TCIG*TFLME-273.15)/XL
C     SUM IS A VARIABLE IN THE HEAT TRANSFER CALCULATION WHICH REPRESENTS
C   THE HEAT FLUX TO THE SUFACE AT A GIVEN TIME M.
C     SURFUS IS THE NON-DIMENSIONAL MASS FLUX FROM THE PROPELLANT SURFACE.
C     SY IS THE AREA BURNING  DURING THE CHAMBER FILLING INTERVAL,( = 1).
C     TAU IS NON-DIMENSIONALIZED TIME
C     TCIG IS THE TEMPERATURE OF THE IGNITER GAS
C     TCRIT IS THE TIME AT WHICH THE NOZZLE BETWEEN THE IGNITER AND MAIN
C     CHAMBERS UNCHOKES. WHEN THIS OCCURS, THE VOLUME OF THE IGNITER NOW
C     AFFECTS THE IGNITION TRANSIENT.
C     TDIFE IS THE AVERAGE TEMPERATURE DIFFERENCE BETWEEN THE CHAMBER
C   GASES AND THE PROPELLANT SURFACE.
C     TEMP IS THE DIMENSIONLESS TEMPERATURE
C     TEMP9 IS THE DIMENSIONAL INITIAL INTERFACE TEMPERATURE.
C     TEMPY IS THE UMCONVERGED VALUE OF THE CHAMBER TEMPERATURE.
C     TFLME IS THE ADIABATIC FLAME TEMPERATURE OF THE PROPELLANT.
C     THA IS THE SQUARE ROOT OF THE TEMPERATURE AT THE PREVIOUS TIME STEP.
C     THERM = DSQRT(ALPHP/3.1416)/XLAMP
C     TIG IS THE IGNITION TEMPERATURE OF THE PROPELLANT
C     TIGNN IS THE NON-DIMENSIONAL TEMPERATURE OF THE IGNITER GAS
C   CALCULATED FROM EXPERIMENTAL IGNITER CSTAR -- ACCCUNTS FOR HEAT
C   LOSSES.
C     TIME IS REAL TIME IN SECONDS.
C     TINT IS THE VALUE OF THE HEAT FLUX AT A GIVEN TIME M.
C     TO IS THE TIME AT WHICH THE IGNITER DECAY BEGINS.
C     TOLER IS THE TOLERANCE IN THE INTEGRATION OF THE DIFFERENTIAL EQUATIONS FO
C   EACH POINT.
C     TREF IS THE CHARACTERISTIC TIME
C     TREF1 IS THE NEW CHARACTERISTIC TIME AFTER THE IGNITER NOZZLE
C   UNCHOKES.
C     TS IS THE SURFACE TEMPERATURE AT A GIVEN POINT ON THE GRAIN
C     TSO IS THE INITIAL SURFACE TEMPERATURE OF THE PROPELLANT IN DEG. C.
C     UCHOKE IS THE TIME AT WHICH THE NOZZLE BETWEEN THE IGNITER AND MAIN
C   CHAMBER UNCHOKES.
C     VISCOS IS THE MASS-WEIGHTED AVERAGE OF THE GAS VISCOSITY.
C     VOL IS THE VOLUME OF THE CHAMBER
C     VOLIGN IS THE VOLUME OF THE IGNITER.
C     WAITAV IS A FUNCTION THAT CALCULATES A WEIGHTED AVERAGE FROM ITS
C   ARGUMENTS.
```

```
C     X IS THE POSITION ON THE PROPELLANT SURFACE WHOSE HEAT INFLUX IS
C   CALCULATED IN 'WARUM'.
C     X1,X2,X3,X4,X5,X6 ARE DUMMY VARIABLES; THEIR VALUES THE COMPUTER
C   OBTAINS FROM WHERE THE FUNCTIONS ARE USED.
C     XL IS THE LENGTH OF THE CHAMBER
C     XLAMG IS THE THERMAL CONDUCTIVITY OF THE PROPELLANT COMBUSTION
C   GASES (CAL/CM-SEC-DEG.C).
C     XLAMGI IS THE THERMAL CONDUCTIVITY OF THE IGNITER GASES.
C     XLAMJ IS ORIGINALLY THE MASS-WEIGHTED AVERAGE OF THE THERMAL
C         CONDUCTIVITIES OF THE IGNITER AND PROPELLANT GASES. AFTER IT
C         IS CALCULATED, IT IS MULTIPLIED BY RXTX(RENUK*TDIFE/XL).
C     XLAMP IS THE THERMAL CONDUCTIVITY OF THE PROPELLANT
C     XLAS IS THE VALUE OF 'X' DURING THE LAST PASS THROUGH 'WARUM'.
C     XMUG IS THE VISCOSITY OF THE PROPELLANT COMBUSTION GASES (G/CM-SEC).
C     XMUGI IS THE VISCOSITY OF THE IGNITER GASES.
C
C   ***************************************************************************
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION CARD(20)
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9 RENUK, XLAMG
      DOUBLE PRECISION      ACROS,   ALD, ALPHP,    DT,  DTIG, GAMSQ,
     1    P9,    PI,    S9, TEMP9,   VOL,VOLIGN, XLAMP
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4
      COMMON       K,     N,   NOS,   ITN
      DATA IDECK/40469/
```

```
C
C  THE FOLLOWING ARE THE FORMAT STATEMENTS USED IN THIS PROGRAM---
C
  100  FORMAT(8F10.0)
  140  FORMAT(I10)
  141  FORMAT(1H1,40X,27HIGNITION TRANSIENT RUN NO. ,I4,15X,9HDECK NO. ,
      1I6)
  145  FORMAT(1H0)
  150  FORMAT(20A4)
  151  FORMAT(1H ,20A4)
  160  FORMAT(1H ,130(1H*))
  209  FORMAT(1H1,/5X,3HTAU,5X,8HPRESSURE,4X,1HS,6X,4HTEMP,3X,9HHEAT FLUX
      1,3X,6HQMSURF,5X,3HGIM,5X,5HDP/DT,3X,5HDT/DT,6X,2HTS,3X,3HITN,2X,4H
      2TIME,4X,6HSURFUS,3X,6HREXOMU,3X,6HCONDUC/)
  210  FORMAT(1H ,2(1PD10.3),1PD8.1,1PD9.2,3(1PD10.3),2(1PD8.1),1PD10.3,
      1I2,4(1PD9.2))
  211  FORMAT(4(1PD10.3),22X,3(1PD10.3),10X,I2,1PD10.3)
  218  FORMAT(1H0,26HCHAMBER FILLING NOW BEGINS)
  400  FORMAT(1H0,10X,17HENGINE PARAMETERS,50X,21HPROPELLANT PARAMETERS/)
  401  FORMAT(1H ,28HEQUILIBRIUM CHAMBER PRESSURE,2X,F9.2,5H PSIA,20X,5HG
      1AMMA,35X,F9.5)
  402  FORMAT(1H ,23HCHARACTERISTIC VELOCITY,7X,F9.2,4H FPS,21X,20HIGNITI
      1ON TEMPERATURE,20X,F9.2,19H DEGREES CENTIGRADE)
  403  FORMAT(1H ,12HGRAIN LENGTH,18X,F9.2,3H CM,22X,32HSOLID PHASE THERM
      1AL CONDUCTIVITY,8X,D13.6,17H CAL/CM-SEC-DEG.C)
  404  FORMAT(1H ,11HGRAIN WIDTH,19X,F9.2,3H CM,22X,30HGAS PHASE THERMAL
      1CONDUCTIVITY,10X,D13.6,17H CAL/CM-SEC-DEG.C)
  405  FORMAT(1H ,14HCHAMBER VOLUME,16X,F9.2,3H CC,22X,19HGAS PHASE VISCO
      1SITY,21X,D13.6,9H G/SEC-CM)
  406  FORMAT(1H ,15HTHROAT DIAMETER,15X,F9.4,7H INCHES,18X,27HADIABATIC
      1FLAME TEMPERATURE,13X,F9.2,15H DEGREES KELVIN)
  407  FORMAT(1H ,25HPORT CROSS-SECTIONAL AREA,5X,F9.4,6H SQ CM,19X,7HDEN
      1SITY,33X,F9.5,5H G/CC)
  408  FORMAT(1H0,10X,14HIGNITER INPUTS,47X,45HNUSSELT NUMBER - REYNOLD'S
      1 NUMBER CORRELATION/)
  409  FORMAT(1H ,22HIGNITER CHAMBER VOLUME,8X,F9.2,3H CC,61X,F6.4)
  410  FORMAT(1H ,25HSTEADY-STATE IGNITER FLOW,5X,F9.5,8H LBM/SEC,39X,5HN
      1UX =,F8.5,4H*REX)
  411  FORMAT(1H ,25HPOINT OF IGNITER TAIL-OFF,5X,F9.3,8H SECONDS)
  412  FORMAT(1H ,17HIGNITER BURN TIME,13X,F9.3,8H SECONDS,30X,18HINITIAL
      1 CONDITIONS)
  413  FORMAT(1H ,23HPROPELLANT LEADING EDGE,7X,F9.5,3H CM,22X,19HTHERMAL
      1 DIFFUSIVITY,21X,D13.6,10H SQ CM/SEC)
  414  FORMAT(1H ,21HEQUILIBRIUM MASS FLOW,9X,F9.5,8H LBM/SEC,17X,17HACTI
      1VATION ENERGY,23X,F9.1,9H CALORIES)
  415  FORMAT(1H ,19HCHARACTERISTIC TIME,11X,F9.5,8H SECONDS,17X,21HSPECI
      1FIC HEAT RELEASE,19X,F9.3,12H CALORIES/GM)
  416  FORMAT(1H ,19H   + IGNITER VOLUME,11X,F9.5,8H SECONDS,17X,28HHEAT
      1RELEASE PRE-EXPONENTIAL,12X,F9.3,7H CM/SEC)
  417  FORMAT(1H ,30HGAS PHASE THERMAL CONDUCTIVITY,F9.6,17H CAL/CM-SEC-D
      1EG.C,8X,30HINITIAL PROPELLANT TEMPERATURE,10X,F9.2,19H DEGREES CEN
      2TIGRADE)
  418  FORMAT(1H ,19HGAS PHASE VISCOSITY,11X,F9.6,9H G/SEC-CM,16X,35HIGNI
      1TER GAS TEMPERATURE WITH LOSSES,5X,F9.2,15H DEGREES KELVIN)
```

```
 419  FORMAT(1H ,26HPOINT OF IGNITER UNCHOKING,4X,F9.3,8H SECONDS,17X,24
     1HINITIAL CHAMBER PRESSURE,16X,F9.3,5H PSIA)
 420  FORMAT(1H ,15HTHROAT DIAMETER,15X,F9.4,7H INCHES)
 421  FORMAT(1H ,64X,26HINITIAL GRAIN AREA IGNITED,17X,F6.1,9H PER CENT)
 422  FORMAT(1H ,5X,35HPROPELLANT BURNING RATE INFORMATION)
 423  FORMAT(1H ,77X,29HQUADRATIC TAIL-OFF EXPRESSION)
 424  FORMAT(1H ,25X,F8.5)
 425  FORMAT(1H ,13X,3HR =,F8.5,2H*P,43X,6HGIM = ,F9.6,7H*T*T + ,F9.6,5H
     1*T + ,F9.6//)
 426  FORMAT(1H ,5X,18HMISCELLANEOUS DATA/)
 427  FORMAT(1H ,59HAVERAGE TEMPERATURE DIFFERENCE BETWEEN SOLID AND GAS
     1 PHASES,2X,F9.2,2X,18HDEGREES CENTIGRADE)
 428  FORMAT(1H ,14HTIME STEP-SIZE,47X,F9.5)
 429  FORMAT(1H ,43HDIFFERENTIAL EQUATION CONVERGENCE TOLERANCE,18X,F9.7
     1)
 500  FORMAT(1H ,'THE STEADY STATE IGNITER FLOW IS ',D13.6,' LBM/SEC')
 990  FORMAT(1H1)
 991  FORMAT(1H0,I4,38H TIME INCREMENTS WERE USED IN THIS RUN)
C     PEQ, CSTAR, XLSTAR, DTIG, DT, ALD, AND GIM ARE IN ENGLISH UNITS
C        ALL OTHER PARAMETERS ARE IN C.G.S. UNITS
      PI = 3.141592653600
      R = 1.987D0
C
      READ (5,140) NORUNS
C   THIS DO-LOOP CYCLES THE PROGRAM THROUGH ALL THE RUNS
C
      DO 111 JHH=1,NORUNS
      DO 135 I=1,2000
      SURFUS(I) = 0.D0
 135  CONTINUE
C     INPUT
C
C        THIS READS THE RUN NUMBER
C
      READ(5,140) IRUN
C
C        THE FOLLOWING IS A COMMENT CARD DESCRIBING THE RUN
C
      READ(5,150) CARD
      READ(5,100) PEQ,DT
      CALL QUADRA(A,B,C,D,TO,FLOW,UCHOKE)
      READ(5,100) DTIG,VOLIGN,XLAMGI,XMUGI
      READ(5,100) WIDTH,XL,VOL,ACROS,ALD
      READ(5,100) GAMMA,TIG,PRODEN,AS,E,Q,TSO,TFLME
      READ(5,100) RENUK,RENUX,XLAMP,XLAMG,ALPHP,XMUG,AN,PREEXP
      READ(5,100) DELT,TOLER,P(1),TEMP(1),S(1),TDIFE
```

```
      DELX = 1.D-3
      ICHECK = 0
      ITN = 0
      JXYZ = 0
      KOUNT = 0
      LINES = 0
      P9 = P(1)
      P(1) = P(1)/PEQ
      QM = 0.D0
      QMSURF = 0.D0
      S9 = S(1)*1.D2
      TAU = 0.D0
      TEMP9 = TEMP(1)
      TEMP(1) = TEMP(1)/TFLME
      TIGNN = TEMP(1)
      XLAS = 0.D0
C
C   THE FOLLOWING ARE 'PROGRAM CONSTANTS'---GROUPS OF TERMS THAT APPEAR
C    IN THE PROGRAM IN VARIOUS LOOPS, ETC. BY CALCULATING THEM NOW, JUST
C    ONCE, SIGNIFICANT COMPUTER TIME IS SAVED.
C
      AL = ALD/XL
      ALPLSX = AL + DELX
C
C   AREABN IN CM.**2 ; WIDTH IN CM. ; XL IN CM.
C
      AREABN = XL*WIDTH
C
      AT = PI*(DT*2.54D0/2.D0)**2
      ATIG = PI*(DTIG*2.54D0/2.0)**2
      CSTAR = PEQ**(1.D0 - AN)*32.174D0*AT/(PRODEN*3.61D-2*AREABN*PREEXP
     1)
      FLEQ = PEQ*AT*32.174D0/(CSTAR*2.54D0*2.54D0)
      GAMSQ = GAMMA*(2.D0/(GAMMA+1.D0))**((GAMMA+1.D0)/(GAMMA-1.D0))
      TREF = VOL/(AT*CSTAR*GAMSQ*30.5D0)
      TREF1 = (VOL + VOLIGN)/(AT*CSTAR*GAMSQ*30.5D0)
      EOVERR = -E/R
      QPA = Q*PRODEN*AS
      REXEQ = PEQ*XL*AT/(CSTAR*ACROS*6.45D0)*1.46D4
      RXTX = RENUK*TDIFE/XL
      SAVEXX = 273.15D0 + TSO
      SCON = RXTX*XLAMGI
      THERM = DSQRT(ALPHP/PI)/XLAMP
      TIG4 = TIG*0.4D0
      TS = TSO
```

```
C       INITIAL OUTPUT
C
        WRITE(6,141) IRUN,IDECK
        WRITE(6,145)
        WRITE(6,160)
        WRITE(6,151) CARD
        WRITE(6,160)
        WRITE(6,400)
        WRITE(6,401) PEQ,GAMMA
        WRITE(6,402) CSTAR,TIG
        WRITE(6,403) XL,XLAMP
        WRITE(6,404) WIDTH,XLAMG
        WRITE(6,405) VOL,XMUG
        WRITE(6,406) DT,TFLME
        WRITE(6,407) ACROS,PRODEN
        WRITE(6,413) ALD,ALPHP
        WRITE(6,414) FLEQ,E
        WRITE(6,415) TREF,Q
        WRITE(6,416) TREF1,AS
        WRITE(6,408)
        WRITE(6,409) VOLIGN,RENUX
        WRITE(6,410) FLOW,RENUK
        WRITE(6,411) TO
        WRITE(6,412) D
        WRITE(6,420) DTIG
        WRITE(6,417) XLAMGI,TSO
        WRITE(6,418) XMUGI,TEMP9
        WRITE(6,419) UCHOKE,P9
        WRITE(6,421) S9
        WRITE(6,422)
        WRITE(6,423)
        WRITE(6,424) AN
        WRITE(6,425) PREEXP,A,B,C
        WRITE(6,426)
        WRITE(6,427) TDIFE
        WRITE(6,428) DELT
        WRITE(6,429) TOLER
        WRITE(6,209)
```

```
C
C          THE TIME AT WHICH THE IGNITER NOZZLE UNCHOKES IS
C        NONDIMENSIONALIZED
C
      UCHOKE = UCHOKE/TREF
      N = 1
C     N ADVANCING CORRESPONDS TO ADVANCING TIME
C     N=1
C
C          THE FIRST POINTS ARE CALCULATED AND VALUES PRINTED OUT
C
      CALL FLOIG
      CALL NXTPNT(JXYZ)
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME
      LINES = 1
      N = 2
      K = 1
C     N GREATER THAN 1
 46   CONTINUE
C
C          TIME IS INCREMENTED
C
      TAU = TAU + DELT
      CALL FLOIG
      CALL NXTPNT(JXYZ)
      IF(JXYZ.NE.0) GO TO 111
C     SELECTION OF THE ELEMENT OF SURFACE TO WHICH HEAT IS TRANSFERRED
      NOS = (S(K)+1.D-4)/DELX
      NOS = NOS + 1
      GO TO 5
 15   CONTINUE
      IF (DABS(S(K)-0.01D0).GT.1.D-4) GO TO 1
C
C          WHEN 1% OF THE GRAIN IS IGNITED, THE GRAIN STEP-SIZE, DELX, IS
C        INCREASED TO 0.01
C
      DELX = 1.D-2
 1    CONTINUE
      NOS = (S(N)+1.D-4)/DELX
      NOS = NOS + 1
 5    CONTINUE
      IF(S(K).LE.0.999D0) GO TO 25
C
C          IF S(1) = 1. , THIS TRANSFERS CONTROL TO THE CHAMBER-FILLING
C        PORTION OF THE PROGRAM
C
      X = 1.D0
      GO TO 24
```

```
 25   CONTINUE
      CALL WARUM
C
C     TEST FOR IGNITION
C
      IF(TS-TIG)23,24,24
C
C     IF THE ELEMENT HAS NOT YET IGNITED -- CALCULATE THE PRESENT
C     CHAMBER CONDITIONS, ADVANCE TIME BY A DELT (BY GOING TO 10
C     -- ADVANCING THE LOOP INDEX, N, BY ONE), AND THEN EXAMINING THE
C     ELEMENT AGAIN
C
 23   CONTINUE
C
C        IF THE ELEMENT HAS NOT IGNITED, THE CURRENT SURFACE BURNING
C       AREA IS EQUAL TO THE PREVIOUS VALUE
C
      S(N) = S(K)
C
C        THIS IS A CHECK TO SEE IF A HANGFIRE HAS OCCURRED
C
      IF (S(N).GT.TOLER) CALL RUNCHK(JXYZ,S,N,DPDT)
      IF(JXYZ.EQ.981) GO TO 111
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME,SURFUS(K),REXOMU(N),CONDUC(N)
      LINES = LINES + 1
      IF (LINES-55) 10,701,701
 701  WRITE(6,209)
      LINES = 0
      GO TO 10
C
C     IF THE ELEMENT HAS IGNITED -- PRINT THE PREVIOUS CHAMBER
C     CONDITIONS WITH THE NEW AREA, AND THEN LOOK AT THE NEXT ELEMENT
C     (BY GOING TO 15).  DO NOT ADVANCE TIME.
C
 24   CONTINUE
      S(N) = X
      S(K) = X
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME,SURFUS(K),REXOMU(N),CONDUC(N)
      LINES = LINES + 1
      IF (LINES-55) 850,851,851
 851  WRITE(6,209)
      LINES = 0
 850  CONTINUE
C
C     TEST FOR END OF FLAME SPREADING
C
      IF(S(N)-0.999D0) 15,28,28
 10   CONTINUE
      K = N
      N = N + 1
      GO TO 46
```

```
C
C       S=1
C
C       SINCE S=1, CHAMBER FILLING NOW BEGINS
C
 28     CONTINUE
        SY = 1.D0
        WRITE(6,218)
        WRITE(6,209)
        LINES = 0
C
C       DOUBLING OF STEP SIZE --
C
        DELT = 2.D0*DELT
C
C       PREPARE DATA FOR CHAMBER FILLING
C
        PLAL = P(N)
        TLAL = TEMP(N)
C
C         SINCE THE TIME INCREMENT HAS BEEN DOUBLED, THE VALUES REQUIRED
C         BY THE PREDICTOR-CORRECTOR METHOD ARE TWO INCREMENTS BACK IN
C         TIME
C
        PLALM1 = P(N-2)
        TLALM1 = TEMP(N-2)
        S(N) = 1.D0
        S(K) = 1.D0
C
C       CHAMBER FILLING CALCULATIONS
C
 32     CONTINUE
C
C          TIME IS INCREMENTED
C
        TAU = TAU + DELT
        K = N
        N = N + 1
        CALL FLOIG
        CALL NXTPNT(JXYZ)
C
C          THIS CHECKS FOR THE CONVERGENCE OF THE INTEGRATION. IF CONVER-
C         GENCE HAS NOT OCCURRED, GO TO THE NEXT RUN
C
        IF(JXYZ.NE.0) GO TO 111
        P(N) = PY
        S(N) = SY
        TEMP(N) = TEMPY
        WRITE(6,211)TAU,PY,SY,TEMPY,GIM,DPDT,DTDT,ITN,TIME
        LINES = LINES + 1
        IF (LINES-55) 852,853,853
 853    WRITE(6,209)
        LINES = 0
 852    CONTINUE
        KOUNT = KOUNT + 1
```

```
C
C      TEST FOR END OF IGNITION TRANSIENT  (I.E. ATTAINMENT OF
C      EQUILIBRIUM PRESSURE)
C
C
C         IF THE NUMBER OF CALCULATIONS HAS EXCEEDED 9000 OR
C        IF |DPDT| < 0.01 AND IF THE PRESSURE IS WITHIN 1% OF ITS
C        EQUILIBRIUM VALUE, TERMINATE THE RUN
C
       IF ((KOUNT.GT.9000).OR.((DABS(PY-1.D0).LE.1.D-2).AND.(DABS(DPDT).L
      1E.1.D-2))) GO TO 34
       GO TO 32
 34    CONTINUE
       WRITE(6,991) N
       WRITE(6,990)
       WRITE(6,990)
 111   CONTINUE
       STOP
       END
```

```
      SUBROUTINE RUNCHK(J,S,N,DPDT)
      DIMENSION S(2000)
      DOUBLE PRECISION          S,  DPDT
      J = 0
C
C        IF S HAS INCREASED BETWEEN TIMES (N-2) AND (N), RESET THE
C       COUNTER. IF NOT, INCREMENT THE COUNTER BY ONE.
C
      IF((S(N)-S(N-2)).GT.1.D-6) GO TO 40
      K = K + 1
      IF((K.LT.100).OR.(DPDT.GT.0.D0)) RETURN
      WRITE(6,3)
 3    FORMAT(1H0,20X,20(1H*),' HANGFIRE -- EXECUTION OF THIS RUN TERMINA
     1TED',1X,20(1H*))
C
C        J IS THE HANGFIRE INDICATOR. IF J=981, A HANGFIRE HAS OCCURRED
C       AND THE RUN IS TERMINATED.
C
      J = 981
 40   CONTINUE
      K = 1
      RETURN
      END
```

```
      SUBROUTINE NXTPNT(JXYZ)
C     SUBROUTINE INTEGRATES THE DIFFERENTIAL EQUATIONS USING A
C     PREDICTOR-CORRECTOR METHOD
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9 RENUK, XLAMG
      DOUBLE PRECISION     GIMOFL,   THA,  TNM2,  PNEW,  TNEW, DPNEW,
     1 DTNEW, DPDTL, DTDTL,  POLD,  TOLD, PPRED, TPRED,  PNM1,  TNM1,
     2  PNM2,    X1,    X2,    X3,    X4,    X5,    X6,WAITAV, PRINCE
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4
      COMMON       K,     N,   NOS,   ITN
C
C  X1,X2,X3,X4,X5,X6 ARE DUMMY VARIABLES; THEIR VALUES THE COMPUTER
C  OBTAINS FROM WHERE THE FUNCTIONS ARE USED.
C
      PRINCE(X1,X2) = DABS(1.D0 - X1/X2) - TOLER
      WAITAV(X3,X4,X5,X6) = (X3*X4 + X5*X6)/(X4 + X6)
C
C        GIMOFL IS THE NONDIMENSIONAL IGNITER FLOW RATE
C
      GIMOFL = GIM/FLEQ
      IF (N-2) 5,15,20
C     S LESS THAN 1
C     INITIAL CONDITIONS -- N=1
  5   CONTINUE
      ETPRES = 0.D0
      ETTEMP = 0.D0
      THA = DSQRT(TEMP(1))
      PN = P(1)**AN
      SURFUS(1) = S(1)*PN
      VISCOS = WAITAV(XMUG,SURFUS(1),XMUGI,GIMOFL)
      REXOMU(N) = REXEQ/VISCOS
      CONDUC(N) = WAITAV(XLAMG,SURFUS(1),XLAMGI,GIMOFL)*RXTX
      DPDT = GAMMA*(SURFUS(1) - P(1)*THA + PMIG)
      DTDT = TEMP(1)*((GAMMA-TEMP(1))*SURFUS(1)/P(1)-(GAMMA-1.D0)*THA
     1+TMIG/P(1))
```

```
      RHELP(1)=(DPDT-P(1)*DTDT/TEMP(1))/TEMP(1)
C
C        THE FIRST POINT HAS BEEN CALCULATED. CONTROL IS RETURNED TO THE
C       MAIN PROGRAM
C
      RETURN
C     N=2  THE SECOND POINT IS CALCULATED USING A MODIFIED RUNGE-KUTTA
C     SCHEME
 15   CONTINUE
C
C        THIS ESTIMATES THE SECOND SET OF POINTS
C
      PNEW = P(K) + DELT*DPDT
      TNEW = TEMP(K) + DELT*DTDT
      PN = PNEW**AN
      THA = DSQRT(TNEW)
C
C    SURFUS IS THE NON-DIMENSIONAL MASS FLUX FROM THE SURFACE OF THE
C        PROPELLANT.
C
      SURFUS(K) = S(K)*PN
      VISCOS = WAITAV(XMUG,SURFUS(K),XMUGI,GIMOFL)
      REXOMU(N) = REXEQ/VISCOS
      CONDUC(N) = WAITAV(XLAMG,SURFUS(K),XLAMGI,GIMOFL)*RXTX
      P(N) = P(K)
      TEMP(N) = TEMP(K)
      DPNEW = GAMMA*(SURFUS(K) - PNEW*THA + PMIG)
      DTNEW=TNEW*((GAMMA-TNEW)*SURFUS(K)/PNEW-(GAMMA-1.D0)*THA+TMIG/PNEW
     1)
      P(N) = P(K) + DELT/2.D0*(DPDT + DPNEW)
      TEMP(N) = TEMP(K) + DELT/2.D0*(DTDT + DTNEW)
      DPDT = DPNEW
      DTDT = DTNEW
      RHELP(N) = (DPDT-P(N)*DTDT/TEMP(N))/TEMP(N)
      RETURN
C
C        THE FIRST TWO POINTS HAVE BEEN CALCULATED. NOW THE PREDICTOR-
C       CORRECTOR METHOD CAN BE USED
C
C     N GREATER THAN TWO
C     TEST FOR END OF FLAME SPREADING
C
 20   IF (S(K) - 0.999D0) 21,80,80
 21   CONTINUE
      ITN = 0
      DPDTL = DPDT
      DTDTL = DTDT
C
C     THE PREDICTOR----
C
      POLD = P(N-2) + 2.D0*DELT*DPDTL
      TOLD = TEMP(N-2) + 2.D0*DELT*DTDTL
      PPRED = POLD
      TPRED = TOLD
```

```
 55   CONTINUE
      PN = POLD**AN
      THA = DSQRT(TOLD)
      SURFUS(K) = S(K)*PN
      VISCOS = WAITAV(XMUG,SURFUS(K),XMUGI,GIMOFL)
      REXOMU(N) = REXEQ/VISCOS
      CONDUC(N) = WAITAV(XLAMG,SURFUS(K),XLAMGI,GIMOFL)*RXTX
      DPDT = GAMMA*(SURFUS(K) - POLD*THA + PMIG)
      DTDT=TOLD*((GAMMA-TOLD)*SURFUS(K)/POLD-(GAMMA-1.D0)*THA+TMIG/POLD)
C
C        THESE ARE THE PREDICTED VALUES. THEY ARE NOW CORRECTED
C
C
C     THE CORRECTOR ---
C
      P(N) = P(K) + DELT/2.D0*(DPDTL + DTDT)
      TEMP(N) = TEMP(K) + DELT/2.D0*(DTDTL + DTDT)
C
C     TEST FOR CONVERGENCE OF INTEGRATION
C
      IF (PRINCE(POLD,P(N))) 62,60,60
 62   IF (PRINCE(TOLD,TEMP(N))) 65,60,60
 60   IF(ITN-10)61,96,96
 61   CONTINUE
      POLD = P(N)
      TOLD = TEMP(N)
      ITN = ITN+1
      GO TO 55
C
C     ETPRES AND ETTEMP ARE THE TRUNCATION ERRORS ACCUMULATED DURING
C     THE INTEGRATION ITERATIONS, ON THE PRESSURE AND TEMP, RESPECTIVELY
C
 65   CONTINUE
      P(N) = P(N) + ETPRES
      TEMP(N) = TEMP(N) + ETTEMP
      ETPRES = 2.D-1*(PPRED-P(N))
      ETTEMP = 2.D-1*(TPRED-TEMP(N))
      RHELP(N) = (DPDT-P(N)*DTDT/TEMP(N))/TEMP(N)
      RETURN
```

```
C
C       S EQUALS ONE -- CHAMBER FILLING INTERVAL
C       INTEGRATING SCHEME SAME AS BEFORE
C       PNM1, PNM2 ARE THE TWO PREVIOUS POINTS.  POLD STARTS AS THE
C       PREDICTED PRESSURE, THEN IS ITERATED WITH PY IN THE CORRECTOR
C       FORMULA.
C
 80     CONTINUE
        PNM1 = PLAL
        TNM1 = TLAL
        PNM2 = PLALM1
        TNM2 = TLALM1
        PN = PNM1**AN
        THA = DSQRT(TNM1)
        DPDTL = GAMMA*(PN - PNM1*THA + PMIG)
        DTDTL=TNM1*((GAMMA-TNM1)*PN/PNM1-(GAMMA-1.)*THA+TMIG/PNM1)
        ITN = 0
        POLD = PNM2 + 2.D0*DELT*DPDTL
        TOLD = TNM2 + 2.D0*DELT*DTDTL
        PPRED = POLD
        TPRED = TOLD
 85     CONTINUE
        PN = POLD**AN
        THA = DSQRT(TOLD)
        CALL FLOIG
        DPDT = GAMMA*(PN - POLD*THA + PMIG)
        DTDT = TOLD*((GAMMA-TOLD)*PN/POLD-(GAMMA-1.D0)*THA + TMIG/POLD)
        PY = PNM1 + DELT/2.D0*(DPDTL + DPDT)
        TEMPY = TNM1 + DELT/2.D0*(DTDTL + DTDT)
        IF (PRINCE(POLD,PY)) 92,90,90
 92     IF (PRINCE(TOLD,TEMPY)) 95,90,90
 90     IF(ITN-10) 91,96,96
 96     CONTINUE
        WRITE(6,250)
 250    FORMAT(1H0,20(1H*),88H PREDICTOR-CORRECTOR SCHEME HAS NOT CONVERGE
       1D AFTER 10 ITERATIONS; EXECUTION TERMINATED ,20(1H*)/)
        JXYZ = 1200
        RETURN
 91     CONTINUE
        POLD = PY
        TOLD = TEMPY
        ITN = ITN + 1
        GO TO 85
C
C          THE ABOVE FIVE STATEMENTS RESTART THE CORRECTOR CYCLE
C
```

```
 95    CONTINUE
       PY = PY + ETPRES
       TEMPY = TEMPY + ETTEMP
       ETPRES = 0.2D0*(PPRED-PY)
       ETTEMP = 0.2D0*(TPRED-TEMPY)
C      STORAGE OF LAST TWO POINTS FOR NEXT TIME AROUND
       PLAL = PY
       TLAL = TEMPY
       PLALM1 = PNM1
       TLALM1 = TNM1
       RETURN
       END
```

```
      SUBROUTINE WARUM
C
C     SUBROUTINE CALCULATES THE TEMPERATURE AT A GIVEN STATION BY
C     INTEGRATING THROUGH TIME THE HEAT TRANSFERRED TO IT
C     THE INTEGRATION IS DONE BY SUMMING AREAS.  THE AREAS ARE EVALUATED
C     AT THE MIDDLE OF THE INTERVAL SO THAT ERRORS TEND TO CANCEL.
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION POTHAF(2000),SQ(2000)
      LOGICAL SAMEAR
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9 RENUK, XLAMG
      DOUBLE PRECISION     POTHAF,  TINT,    SQ,ONEMIX,   SUM,    Q1,
     1 TERM1, TERM2,  DIFF
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4
      COMMON       K,     N,   NOS,   ITN
C
C    THE SURFACE HEAT RELEASE EQUATION HAS THE FORM
C      QMSURF = Q*PRODEN*AS*EXP(-E/(R*(TS + 273.15))) , WHERE
C    Q IS AN EMPIRICAL CONSTANT, PRODEN IS THE PROPELLANT DENSITY, AS IS
C  A DIMENSIONALIZING BURNING RATE FOR THE EXPONENTIAL TERM, E IS THE
C  ACTIVATION ENERGY OF THE PROPELLANT, R IS THE UNIVERSAL GAS CONSTANT,
C  AND TS IS THE TEMPERATURE OF THE SURFACE OF THE PROPELLANT, IN
C  DEGREES CENTIGRADE.
C
C
C        X IS THE GRAIN ELEMENT BEING EXAMINED
C
      X = DFLOAT(NOS)*DELX
      POTHAF(K) = P(K)/DSQRT(TEMP(K))
      IF(DFLOAT(K)*DELT.GT.UCHOKE) GO TO 150
      CHAR = TREF
      GO TO 200
  150 CONTINUE
      CHAR = TREF1
  200 CONTINUE
```

```
C
C         THE CHARACTERISTIC TIME TO BE USED IS DETERMINED BY WHETHER OR
C       NOT THE IGNITER HAS UNCHOKED
C
      SQ(K) = DSQRT(CHAR/TAU)
      IF(DABS(XLAS-X).GT.TOLER) GO TO 5
C
C         IF X IS THE SAME AS THE PREVIOUS VALUE, THE FOLLOWING
C       CALCULATIONS CAN BE OMITTED
C
      REX = REXOMU(K)*ALPLSX*(POTHAF(K) + ONEMIX*RHELP(K))
      QMCONV(K) = CONDUC(K)/ALPLSX*REX**RENUX
C
C         SAMEAR = 'SAME AREA'
C
      SAMEAR = .TRUE.
      GO TO 30
 5    CONTINUE
      ALPLSX = ALPLSX + DELX
      ONEMIX = 1.DO - X
      SAMEAR = .FALSE.
C
C         NOW WE ARE AT A NEW AREA
C
 30   CONTINUE
      SUM = 0.DO
      REX = REXEQ*ALPLSX*(POTHAF(1)+ONEMIX *RHELP(1))/XMUGI
C        SCON = RENUK*XLAMG*(TCIG*TFLME-273.15)/XL
      Q1 = SCON*REX**RENUX/ALPLSX
      QM = Q1
      TERM1 = DSQRT(TREF/TAU)*QM
      SUM = DELT*TERM1
      QMSURF = 0.DO
      DIFF = TAU
      IF (N - 3) 35,10,10
 10   CONTINUE
C
C         THIS LOOP INTEGRATES THE HEAT FLUX THROUGH TIME TO GET THE
C       SURFACE TEMPERATURE
C
C     HERE ADVANCING M CORRESPONDS TO ADVANCING TIME.
C
```

```
      DO 20 M=2,K
      DIFF = DIFF - DELT
C
C        IF THE SAME X AS IN THE PREVIOUS PASS THROUGH THE SUBROUTINE IS
C       BEING EXAMINED, THE NEXT TWO STATEMENTS ARE BYPASSED
C
      IF (SAMEAR) GO TO 40
      REX = REXOMU(M)*ALPLSX*(POTHAF(M) + ONEMIX*RHELP(M))
      QMCONV(M) = CONDUC(M)/ALPLSX*REX**RENUX
 40   CONTINUE
      QM = QMCONV(M) + QMSURF
      TERM2 = SQ(N-M)*QM
      TINT = (TERM2 + TERM1)/2.DO
      TERM1 = TERM2
      SUM = SUM + DELT*TINT
      TS = THERM*SUM
C
C        IF THE SURFACE TEMPERATURE IS LESS THAN 40% OF THE IGNITION
C       TEMPERATURE, THE SURFACE HEAT RELEASE TERM NEED NOT BE
C       CALCULATED
C
      IF(TS.LT.TIG4) GO TO 20
C
C  QPA = Q*PRODEN*AS
C  EOVERR = -E/R .
C  SAVEXX = 273.15 + TSO
C
      QMSURF = QPA*DEXP(EOVERR/(TS+SAVEXX))
 20   CONTINUE
      TINT = DSQRT(2.DO*CHAR/DELT)*QM
      SUM = SUM + DELT*TINT
 35   CONTINUE
      TS = TSO + THERM*SUM
      XLAS = X
      RETURN
      END
```

```
      SUBROUTINE FLOIG
C
C     SUBROUTINE SUPPLIES THE IGNITER EFFECTS
C  'T' IS THE REAL TIME, IN SECONDS.
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DOUBLE PRECISION      TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,    GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,   DTDT,     AN,
     4  TOLER,     PY,ETPRES, TFLME,   PLAL,   TLAL,PLALM1,TLALM1, CONST,
     5   BCON,   SCON,CSTARI,      A,      B,      C,      D,     TO,PRODEN,
     6     AS,      E,      R,  TIME,  RXTX,    QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   CHAR,   FLEQ, TIGNN,VISCOS,   XLAS,   TIG4,
     9 RENUK, XLAMG
      DOUBLE PRECISION      DSQRT,   DABS,   DEXP,DFLOAT,   DLOG
      COMMON   RENUK, XLAMG, TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,    GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,   DTDT,     AN,
     4  TOLER,     PY,ETPRES, TFLME,   PLAL,   TLAL,PLALM1,TLALM1, CONST,
     5   BCON,   SCON,CSTARI,      A,      B,      C,      D,     TO,PRODEN,
     6     AS,      E,      R,  TIME,  RXTX,    QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   FLEQ, TIGNN,   XLAS,   TIG4
      COMMON       K,      N,    NOS,    ITN
      IF(TAU.LT.UCHOKE) GO TO 800
C
C        IF THE IGNITER HAS UNCHOKED, THE CHARACTERISTIC TIME HAS
C       INCREASED DUE TO THE ADDITIONAL VOLUME
C
      TIME = UCHOKE*TREF + (TAU - UCHOKE)*TREF1
      GO TO 801
  800 CONTINUE
      TIME = TAU*TREF
  801 CONTINUE
C
C  THE NEXT THREE STATEMENTS EXPRESS THE IGNITER MASS FLOW RATE AS A
C FUNCTION OF TIME--THE SECOND STATEMENT, WHICH IS A QUADRATICALLY
C DECREASING FUNCTION, USING THE FOLLOWING AS INPUT CONSTANTS... A,B,C,
C D,TO.
C
      IF (TIME.LT.TO) GIM = FLOW
      IF ((TIME.GT.TO).AND.(TIME.LT.D)) GIM = C + TIME*(B + TIME*A)
      IF (TIME.GT.D) GIM = 0.0
      PMIG = TIGNN*GIM/FLEQ
      IF (N.EQ.1) GO TO 901
      TMIG = PMIG/TIGNN*(GAMMA*TIGNN - TEMP(K))
      RETURN
  901 CONTINUE
      TMIG = PMIG/TIGNN*(GAMMA*TIGNN - TEMP(1))
      RETURN
      END
```

```
      SUBROUTINE QUADRA(A,B,C,D,TO,FLOW,UCHOKE)
C  GIVEN THREE POINTS AS INPUT, THIS SUBROUTINE CALCULATES THE COEFFI-
C  CIENTS IN THE QUADRATIC EXPRESSION FOR THE IGNITER TAIL-OFF IN
C  SUBROUTINE 'FLOIG'.
      DOUBLE PRECISION          X,     Y,     A,     B,     C,     Z,
     1     D,    TO,  FLOW,UCHOKE
      DIMENSION X(3),Y(3)
      READ(5,100) X,Y,UCHOKE
  100 FORMAT(8F10.0)
      Z = (Y(2)-Y(1))/(X(2)-X(1))
      A = ((Y(3)-Y(1))/(X(3)-X(1))-Z)/(X(3)-X(2))
      B = Z-A*(X(2)+X(1))
      C = Y(1)-A*X(1)**2-B*X(1)
      FLOW = Y(1)
      TO = X(1)
      D = X(3)
      RETURN
      END
```

```
C
C
C
C                                   COMMENTS
C
C
C
C
C
C
C
C
C
C
C
C
C
C     PROGRAM NAME ---- PPSPIG2, FOR PRESSURE PREDICTION OF
C     SOLID PROPELLANT IGNITION, PROGRAM #2.
C
C          THE FOLLOWING PEOPLE HAVE CONTRIBUTED TO THIS PROGRAM ---
C
C       KIM H. PARKER
C       WILLIAM J. MOST
C       GERALD F. DILAURO
C       LAWRENCE H. LINDEN
C       BRUCE W. MACDONALD
C
C
C
C
C                   NOMENCLATURE
C
C                         NOTE : NOT ALL OF THE NOMENCLATURE IN THIS
C                         LIST IS USED IN ANY GIVEN PROGRAM. SOME
C                         NOTATION REFERS TO ALTERNATIVE SUBROUTINES.
C
C   ***************************************************************************
C     A,B,C ARE CONSTANTS IN THE QUADRATIC EQUATION FOR THE IGNITER TAIL-
C   OFF IN SUBROUTINE "FLOIG".
C     ACONST = PCIG*ATIG/(DSQRT(TCIG)*AT)
C     ACROS IS THE PORT CROSS-SECTIONAL AREA OF THE MAIN CHAMBER (CM**2).
C     AL IS THE NON-DIMENSIONAL ALD.
C     ALD IS THE LENGTH OF THE BOUNDARY LAYER LEADING EDGE AHEAD OF THE
C   PROPELLANT LEADING EDGE (CM).
C     ALPHP IS THE THERMAL DIFFUSIVITY OF THE PROPELLANT (CM**2/SEC).
C     ALPLSX = AL + X
C     AN IS THE EXPONENT IN THE BURNING RATE LAW.
C     AS IS THE PRE-EXPONENTIAL IN BR = AS*EXP(E/(R*TS)) (CM/SEC).
C     AT IS THE EXHAUST NOZZLE AREA (CM**2).
C     ATIG IS THE IGNITER NOZZLE AREA (CM**2).
C     BR IS THE BURNING RATE (IN/SEC).
C     BCON = P(1)/DSQRT(TEMP(1)).
C     CONDUC IS THE MASS-WEIGHTED AVERAGE OF THE THERMAL CONDUCTIVITIES
C   OF THE IGNITER AND PROPELLANT GASES MULTIPLIED BY RXTX.
```

```
C     CONST = GAMMA*TCIG OR GAMMA*TIGNN IF THE NON-ADIABATICITY OF THE
C   IGNITER FLOW IS KNOWN.
C     CSTAR IS THE MOTOR CHARACTERISTIC VELOCITY IN FEET PER SECOND.
C     CSTARI IS THE IGNITER CHARACTERISTIC VELOCITY IN FEET PER SECOND.
C   IT CAN BE BASED ON TCIG OR TIGNN. THE CHOICE MUST BE SPECIFIED AND
C   USED ACCORDINGLY.
C     D IS THE TIME AT WHICH GIM = 0.0 (SEC).
C     DELREF = DELT*TREF (SECONDS).
C     DELT IS THE INCREMENT OF TAU -- USUALLY 0.03 UNITS.
C     DELX IS THE INCREMENT OF GRAIN LENGTH -- USUALLY 0.01.
C     DIFF IS A DUMMY TIME VARIABLE USED IN  SUBROUTINE "WARUM".
C     DPDT IS THE NON-DIMENSIONAL DERIVATIVE OF PRESSURE W.R.T. TIME.
C     DTDT IS THE NON-DIMENSIONAL DERIVATIVE OF TEMPERATURE W.R.T. TIME.
C     DT IS THE EXHAUST THROAT DIAMETER (IN).
C     DTIG IS THE IGNITER THROAT DIAMETER (IN).
C     E IS THE ACTIVATION ENERGY OF THE PROPELLANT (CAL/MOLE).
C     EOVERR IS THE ACTIVATION ENERGY E DIVIDED BY THE GAS CONSTANT R.
C     ETPRES,ETTEMP ARE THE TRUNCATION ERRORS IN CALCULATING 'P' AND 'T'
C   USING THE PREDICTOR-CORRECTOR METHOD.
C     FLEQ IS THE EQUILIBRIUM MASS-FLOW RATE (LBM/SEC).
C     FLOW IS THE IGNITER MASS FLOW RATE BEFORE THE QUADRATIC TAILOFF
C   IN LBM/SEC.
C     GAMMA IS THE RATIO OF SPECIFIC HEATS.
C     GAMSQ IS A FUNCTION OF GAMMA, = GAMMA*(2./(GAMMA-1.)**(GAMMA+1.)/
C   (GAMMA-1.)
C     GIM IS THE IGNITER MASS FLOW RATE AT ANY TIME (LBM/SEC).
C     GIMOFL IS THE NON-DIMENSIONAL IGNITER MASS FLOW RATE.
C     ITN IS THE NUMBER OF ITERATIONS USED IN EACH TIME STEP IN
C   SUBROUTINE 'NXTPNT'.
C     JXYZ IS A VARIABLE WHICH ACTS AS A SIGNAL THAT TERMINATES EXECUTION
C   OF A RUN IF : 1) THERE IS A HANGFIRE, OR 2) THE INTEGRATION OF THE
C   DIFFERENTIAL EQUATIONS IS NOT CONVERGING.
C     KOUNT KEEPS THE PROGRAM FROM GETTING 'HUNG UP' IN PERFORMING AN
C   INFINITE NUMBER OF TIME INCREMENTS.
C     LALL IS A TIME COUNTER.
C     NOS IS THE INTEGRAL NUMBER OF IGNITED SURFACE ELEMENTS.
C     NUX IS THE NUSSELT NUMBER AT A GIVEN POSITION X.
C     ONEMIX = 1. - X
C     P IS THE NON-DIMENSIONAL CHAMBER PRESSURE.
C     POTHAF = P(K)/DSQRT(TEMP(K)). THIS IS SIMPLY A CONSTANT USED IN
C   THE HEAT TRANSFER SUBROUTINE.
C     P9 IS THE DIMENSIONAL INITIAL PRESSURE.
C     PCIG IS THE NON-DIMENSIONAL PRESSURE IN THE IGNITER CHAMBER.
C     PEQ IS THE EQUILIBRIUM CHAMBER PRESSURE IN PSIA. IT CAN BE TAKEN
C   AS EITHER THE THEORETICAL OR EXPERIMENTAL VALUE.
C     PI = 3.1415926536
C     PMIG = TIGNN*GIM/FLEQ OR TCIG*GIM/FLEQ.
C     PN IS THE NON-DIMENSIONAL BURNING RATE, = P**AN.
C     PRINCE IS A TEST FOR THE CONVERGENCE OF THE INTEGRATION OF THE
C   DIFFERENTIAL EQUATIONS.
C     PRODEN IS THE PROPELLANT DENSITY IN GM/CM**3.
C     PY IS AN INTERMEDIATE NON-CONVERGED VALUE OF 'P'.
C     Q IS THE VOLUMETRIC HEAT RELEASE ASSIGNED TO THE SURFACE, IN CAL/GM.
C     Q1 IS THE TOTAL HEAT FLUX AT TAU = DEL, IN CAL/CM**2*SEC.
C     QM IS THE TOTAL HEAT FLUX AT TIME M, IN CAL/(CM**2*SEC).
```

```
C     QMCONV IS THE CONVECTIVE HEAT FLUX AT TIME M, IN CAL/(CM**2*SEC).
C     QPA IS THE PRE-EXPONENTIAL IN THE SURFACE HEAT RELEASE EQUATION,
C   = Q*PRODEN*AS.
C     QMSURF IS THE SURFACE HEAT RELEASE, IN CAL/(CM**2*SEC).
C     RENUK IS THE REYNOLD'S NUMBER COEFFICIENT.
C     RENUX IS THE REYNOLD'S NUMBER EXPONENT.
C     REX IS THE REYNOLD'S NUMBER AT GRAIN POSITION X.
C     REXEQ IS THE EQUILIBRIUM REYNOLD'S NUMBER,@ X = XL.
C   NUMBER.
C     REXOMU IS THE GAS VISCOSITY DIVIDED INTO THE EQUILIBRIUM REYNOLD'S
C     RHELP IS THE MASS STORAGE TERM IN REX, AND IS EQUAL TO THE
C   DERIVATIVE OF PRESSURE DIVIDED BY TEMPERATURE WITH RESPECT TO TIME.
C     RXTX = RENUK*TDIFE/XL.
C     S IS THE NON-DIMENSIONAL AREA ALREADY IGNITED.
C     S9 IS THE PER CENTAGE OF GRAIN SURFACE IGNITED.
C     SAVEXX IS THE INITIAL PROPELLANT TEMPERATURE CONVERTED TO KELVIN.
C     SCON = RENUK*XLAMG*(TCIG*TFLME-273.15)/XL
C     SUM IS A VARIABLE IN THE HEAT TRANSFER CALCULATION WHICH REPRESENTS
C   THE HEAT FLUX TO THE SUFACE AT A GIVEN TIME M.
C     SURFUS IS THE NON-DIMENSIONAL MASS FLUX FROM THE PROPELLANT SURFACE.
C     SY IS THE AREA BURNING  DURING THE CHAMBER FILLING INTERVAL, ( = 1).
C     TAU IS NON-DIMENSIONALIZED TIME
C     TCIG IS THE TEMPERATURE OF THE IGNITER GAS
C     TCRIT IS THE TIME AT WHICH THE NOZZLE BETWEEN THE IGNITER AND MAIN
C     CHAMBERS UNCHOKES. WHEN THIS OCCURS, THE VOLUME OF THE IGNITER NOW
C     AFFECTS THE IGNITION TRANSIENT.
C     TDIFE IS THE AVERAGE TEMPERATURE DIFFERENCE BETWEEN THE CHAMBER
C   GASES AND THE PROPELLANT SURFACE.
C     TEMP IS THE DIMENSIONLESS TEMPERATURE
C     TEMP9 IS THE DIMENSIONAL INITIAL INTERFACE TEMPERATURE.
C     TEMPY IS THE UMCONVERGED VALUE OF THE CHAMBER TEMPERATURE.
C     TFLME IS THE ADIABATIC FLAME TEMPERATURE OF THE PROPELLANT.
C     THA IS THE SQUARE ROOT OF THE TEMPERATURE AT THE PREVIOUS TIME STEP.
C     THERM = DSQRT(ALPHP/3.1416)/XLAMP
C     TIG IS THE IGNITION TEMPERATURE OF THE PROPELLANT
C     TIGNN IS THE NON-DIMENSIONAL TEMPERATURE OF THE IGNITER GAS
C   CALCULATED FROM EXPERIMENTAL IGNITER CSTAR -- ACCCUNTS FOR HEAT
C   LOSSES.
C     TIME IS REAL TIME IN SECONDS.
C     TINT IS THE VALUE OF THE HEAT FLUX AT A GIVEN TIME M.
C     TO IS THE TIME AT WHICH THE IGNITER DECAY BEGINS.
C     TOLER IS THE TOLERANCE IN THE INTEGRATION OF THE DIFFERENTIAL EQUATIONS FOR
C   EACH POINT.
C     TREF IS THE CHARACTERISTIC TIME
C     TREF1 IS THE NEW CHARACTERISTIC TIME AFTER THE IGNITER NOZZLE
C   UNCHOKES.
C     TS IS THE SURFACE TEMPERATURE AT A GIVEN POINT ON THE GRAIN
C     TSO IS THE INITIAL SURFACE TEMPERATURE OF THE PROPELLANT IN DEG. C.
C     UCHOKE IS THE TIME AT WHICH THE NOZZLE BETWEEN THE IGNITER AND MAIN
C   CHAMBER UNCHOKES.
C     VISCOS IS THE MASS-WEIGHTED AVERAGE OF THE GAS VISCOSITY.
C     VOL IS THE VOLUME OF THE CHAMBER
C     VOLIGN IS THE VOLUME OF THE IGNITER.
C     WAITAV IS A FUNCTION THAT CALCULATES A WEIGHTED AVERAGE FROM ITS
C   ARGUMENTS.
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C     X IS THE POSITION ON THE PROPELLANT SURFACE WHOSE HEAT INFLUX IS
C   CALCULATED IN 'WARUM'.
C     X1,X2,X3,X4,X5,X6 ARE DUMMY VARIABLES; THEIR VALUES THE COMPUTER
C   OBTAINS FROM WHERE THE FUNCTIONS ARE USED.
C     XL IS THE LENGTH OF THE CHAMBER
C     XLAMG IS THE THERMAL CONDUCTIVITY OF THE PROPELLANT COMBUSTION
C   GASES (CAL/CM-SEC-DEG.C).
C     XLAMGI IS THE THERMAL CONDUCTIVITY OF THE IGNITER GASES.
C     XLAMJ IS ORIGINALLY THE MASS-WEIGHTED AVERAGE OF THE THERMAL
C         IS CALCULATED, IT IS MULTIPLIED BY RXTX(RENUK*TDIFE/XL).
C     XLAMP IS THE THERMAL CONDUCTIVITY OF THE PROPELLANT
C     XLAS IS THE VALUE OF 'X' DURING THE LAST PASS THROUGH 'WARUM'.
C     XMUG IS THE VISCOSITY OF THE PROPELLANT COMBUSTION GASES (G/CM-SEC).
C     XMUGI IS THE VISCOSITY OF THE IGNITER GASES.
C
C   ***************************************************************************
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION PRES(100),BRATE(100),RATE(99)
      DIMENSION CARD(20)
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ, RENUK, XLAMG
      DOUBLE PRECISION      ACROS,   ALD, ALPHP,    DT,  DTIG, GAMSQ,
     1   P9,    PI,    S9, TEMP9,   VOL,VOLIGN, XLAMP
      DOUBLE PRECISION        PN
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ,PREEXP
      COMMON       N,     K,   NOS,   ITN
      COMMON NPOINT
      DATA IDECK/40669/
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```
C
C  THE FOLLOWING ARE THE FORMAT STATEMENTS USED IN THIS PROGRAM---
C
  100  FORMAT(8F10.0)
  140  FORMAT(I10)
  141  FORMAT(1H1,40X,27HIGNITION TRANSIENT RUN NO. ,I4,15X,9HDECK NO. ,
     1I6)
  145  FORMAT(1H0)
  150  FORMAT(20A4)
  151  FORMAT(1H ,20A4)
  160  FORMAT(1H ,130(1H*))
  209  FORMAT(1H1,/5X,3HTAU,5X,8HPRESSURE,4X,1HS,6X,4HTEMP,3X,9HHEAT FLUX
     1,3X,6HQMSURF,5X,3HGIM,5X,5HDP/DT,3X,5HDT/DT,6X,2HTS,3X,3HITN,2X,4H
     2TIME,4X,6HSURFUS,3X,6HREXGMU,3X,6HCONDUC/)
  210  FORMAT(1H ,2(1PD10.3),1PD8.1,1PD9.2,3(1PD10.3),2(1PD8.1),1PD10.3,
     1I2,4(1PD9.2))
  211  FORMAT(4(1PD10.3),22X,3(1PD10.3),10X,I2,1PD10.3)
  218  FORMAT(1H0,26HCHAMBER FILLING NOW BEGINS)
  400  FORMAT(1H0,10X,17HENGINE PARAMETERS,50X,21HPROPELLANT PARAMETERS/)
  401  FORMAT(1H ,28HEQUILIBRIUM CHAMBER PRESSURE,2X,F9.2,5H PSIA,20X,5HG
     1AMMA,35X,F9.5)
  402  FORMAT(1H ,23HCHARACTERISTIC VELOCITY,7X,F9.2,4H FPS,21X,20HIGNITI
     1ON TEMPERATURE,20X,F9.2,19H DEGREES CENTIGRADE)
  403  FORMAT(1H ,12HGRAIN LENGTH,18X,F9.2,3H CM,22X,32HSOLID PHASE THERM
     1AL CONDUCTIVITY,8X,D13.6,17H CAL/CM-SEC-DEG.C)
  404  FORMAT(1H ,11HGRAIN WIDTH,19X,F9.2,3H CM,22X,30HGAS PHASE THERMAL
     1CONDUCTIVITY,10X,D13.6,17H CAL/CM-SEC-DEG.C)
  405  FORMAT(1H ,14HCHAMBER VOLUME,16X,F9.2,3H CC,22X,19HGAS PHASE VISCO
     1SITY,21X,D13.6,9H G/SEC-CM)
  406  FORMAT(1H ,15HTHROAT DIAMETER,15X,F9.4,7H INCHES,18X,27HADIABATIC
     1FLAME TEMPERATURE,13X,F9.2,15H DEGREES KELVIN)
  407  FORMAT(1H ,25HPORT CROSS-SECTIONAL AREA,5X,F9.4,6H SQ CM,19X,7HDEN
     1SITY,33X,F9.5,5H G/CC)
  408  FORMAT(1H0,10X,14HIGNITER INPUTS,47X,45HNUSSELT NUMBER - REYNOLD'S
     1 NUMBER CORRELATION/)
  409  FORMAT(1H ,22HIGNITER CHAMBER VOLUME,8X,F9.2,3H CC,61X,F6.4)
  410  FORMAT(1H ,25HSTEADY-STATE IGNITER FLOW,5X,F9.5,8H LBM/SEC,39X,5HN
     1UX =,F8.5,4H*REX)
  411  FORMAT(1H ,25HPOINT OF IGNITER TAIL-OFF,5X,F9.3,8H SECONDS)
  412  FORMAT(1H ,17HIGNITER BURN TIME,13X,F9.3,8H SECONDS,30X,18HINITIAL
     1 CONDITIONS)
  413  FORMAT(1H ,23HPROPELLANT LEADING EDGE,7X,F9.5,3H CM,22X,19HTHERMAL
     1 DIFFUSIVITY,21X,D13.6,10H SQ CM/SEC)
  414  FORMAT(1H ,21HEQUILIBRIUM MASS FLOW,9X,F9.5,8H LBM/SEC,17X,17HACTI
     1VATION ENERGY,23X,F9.1,9H CALORIES)
  415  FORMAT(1H ,19HCHARACTERISTIC TIME,11X,F9.5,8H SECONDS,17X,21HSPECI
     1FIC HEAT RELEASE,19X,F9.3,12H CALORIES/GM)
  416  FORMAT(1H ,19H   + IGNITER VOLUME,11X,F9.5,8H SECONDS,17X,28HHEAT
     1RELEASE PRE-EXPONENTIAL,12X,F9.3,7H CM/SEC)
  417  FORMAT(1H ,30HGAS PHASE THERMAL CONDUCTIVITY,F9.6,17H CAL/CM-SEC-D
     1EG.C,8X,30HINITIAL PROPELLANT TEMPERATURE,10X,F9.2,19H DEGREES CEN
     2TIGRADE)
  418  FORMAT(1H ,19HGAS PHASE VISCOSITY,11X,F9.6,9H G/SEC-CM,16X,35HIGNI
     1TER GAS TEMPERATURE WITH LOSSES,5X,F9.2,15H DEGREES KELVIN)
```

```
  419  FORMAT(1H ,26HPOINT OF IGNITER UNCHOKING,4X,F9.3,8H SECONDS,17X,24
     1HINITIAL CHAMBER PRESSURE,16X,F9.3,5H PSIA)
  420  FORMAT(1H ,15HTHROAT DIAMETER,15X,F9.4,7H INCHES)
  421  FORMAT(1H ,64X,26HINITIAL GRAIN AREA IGNITED,17X,F6.1,9H PER CENT)
  422  FORMAT(1H ,5X,35HPROPELLANT BURNING RATE INFORMATION/)
  423  FORMAT(1H ,77X,29HQUADRATIC TAIL-OFF EXPRESSION)
  426  FORMAT(1H ,10X,18HMISCELLANEOUS DATA)
  427  FORMAT(1H ,38HAVERAGE TEMPERATURE DIFFERENCE BETWEEN)
  428  FORMAT(1H ,14HTIME STEP SIZE,36X,F9.5,14X,6HGIM = ,F8.5,7H*T*T + ,
     1F8.5,5H*T + ,F8.5)
  429  FORMAT(1H ,43HDIFFERENTIAL EQUATION CONVERGENCE TOLERANCE,7X,F9.7)
  430  FORMAT(1H ,14X,F9.3,12X,F9.5)
  431  FORMAT(1H ,11X,15HPRESSURE (PSIA),5X,26H BURNING RATE (INCHES/SEC)
     1/)
  433  FORMAT(1H ,21HSOLID AND GAS PHASES ,29X,F9.2,19H DEGREES CENTIGRAD
     1E/)
  500  FORMAT(1H ,'THE STEADY STATE IGNITER FLOW IS ',D13.6,' LBM/SEC')
  990  FORMAT(1H1)
  991  FORMAT(1HO,I4,38H TIME INCREMENTS WERE USED IN THIS RUN)
C      PEQ, CSTAR, XLSTAR, DTIG, DT, ALD, AND GIM ARE IN ENGLISH UNITS
C         ALL OTHER PARAMETERS ARE IN C.G.S. UNITS
       PI = 3.141592653600
       R = 1.987D0
C
       READ (5,140) NORUNS
C    THIS DO-LOOP CYCLES THE PROGRAM THROUGH ALL THE RUNS
C
       DO 111 JHH=1,NORUNS
       DO 135 I=1,2000
       SURFUS(I) = 0.D0
  135  CONTINUE
C
C      INPUT
C
C
C         THIS READS THE RUN NUMBER
C
       READ(5,140) IRUN
C
C         THE FOLLOWING IS A COMMENT CARD DESCRIBING THE RUN
C
       READ(5,150) CARD
       READ(5,100) PEQ,DT
       CALL QUADRA(A,B,C,D,TO,FLOW,UCHOKE)
       READ(5,140) NPOINT
       DO 130 I=1,NPOINT
       READ(5,100) PRES(I),BRATE(I)
  130  CONTINUE
       READ(5,100) DTIG,VOLIGN,XLAMGI,XMUGI
       READ(5,100) WIDTH,XL,VOL,ACROS,ALD
       READ(5,100) GAMMA,TIG,PRODEN,AS,E,Q,TSO,TFLME
       READ(5,100) RENUK,RENUX,XLAMP,XLAMG,ALPHP,XMUG
       READ(5,100) DELT,TOLER,P(1),TEMP(1),S(1),TDIFE
```

```
C
C         CALCULATE THE EXPONENTS USED IN THE FUNCTION "PN".
C
      REQ = 1.D0
      NPO = NPOINT - 1
      DO 6 I=1,NPO
      RATE(I) = DLOG(BRATE(I+1)/BRATE(I))/DLOG(PRES(I+1)/PRES(I))
 6    CONTINUE
      REQ = PN(PEQ)
      DELX = 1.D-3
      ITN = 0
      JXYZ = 0
      KOUNT = 0
      LINES = 0
      P9 = P(1)
      P(1) = P(1)/PEQ
      QM = 0.D0
      QMSURF = 0.D0
      S9 = S(1)*1.D2
      TAU = 0.D0
      TEMP9 = TEMP(1)
      TEMP(1) = TEMP(1)/TFLME
      TIGNN = TEMP(1)
      XLAS = 0.D0
C   THE FOLLOWING ARE 'PROGRAM CONSTANTS'---GROUPS OF TERMS THAT APPEAR
C    IN THE PROGRAM IN VARIOUS LOOPS, ETC. BY CALCULATING THEM NOW, JUST
C    ONCE, SIGNIFICANT COMPUTER TIME IS SAVED.
C
      AL = ALD/XL
      ALPLSX = AL + DELX
C
C   AREABN IN CM.**2 ; WIDTH IN CM. ; XL IN CM.
C
      AREABN = XL*WIDTH
C
      AT = PI*(DT*2.54D0/2.D0)**2
      ATIG = PI*(DTIG*2.54D0/2.0)**2
      CSTAR = PEQ*32.174D0*AT/(PRODEN*3.61D-2*AREABN*REQ)
      FLEQ = PEQ*AT*32.174D0/(CSTAR*2.54D0*2.54D0)
      GAMSQ = GAMMA*(2.D0/(GAMMA+1.D0))**((GAMMA+1.D0)/(GAMMA-1.D0))
      TREF = VOL/(AT*CSTAR*GAMSQ*30.5D0)
      TREF1 = (VOL + VOLIGN)/(AT*CSTAR*GAMSQ*30.5D0)
      EOVERR = -E/R
      QPA = Q*PRODEN*AS
      REXEQ = PEQ*XL*AT/(CSTAR*ACROS*6.45D0)*1.46D4
      RXTX = RENUK*TDIFE/XL
      SAVEXX = 273.15D0 + TSO
      SCON = RXTX*XLAMGI
      THERM = DSQRT(ALPHP/PI)/XLAMP
      TIG4 = TIG*0.4D0
      TS = TSO
```

```
C
C       INITIAL OUTPUT
C
        WRITE(6,141) IRUN,IDECK
        WRITE(6,145)
        WRITE(6,160)
        WRITE(6,151) CARD
        WRITE(6,160)
        WRITE(6,400)
        WRITE(6,401) PEQ,GAMMA
        WRITE(6,402) CSTAR,TIG
        WRITE(6,403) XL,XLAMP
        WRITE(6,404) WIDTH,XLAMG
        WRITE(6,405) VOL,XMUG
        WRITE(6,406) DT,TFLME
        WRITE(6,407) ACROS,PRODEN
        WRITE(6,413) ALD,ALPHP
        WRITE(6,414) FLEQ,E
        WRITE(6,415) TREF,Q
        WRITE(6,416) TREF1,AS
        WRITE(6,408)
        WRITE(6,409) VOLIGN,RENUX
        WRITE(6,410) FLOW,RENUK
        WRITE(6,411) TO
        WRITE(6,412) D
        WRITE(6,420) DTIG
        WRITE(6,417) XLAMGI,TSO
        WRITE(6,418) XMUGI,TEMP9
        WRITE(6,419) UCHOKE,P9
        WRITE(6,421) S9
        WRITE(6,426)
        WRITE(6,423)
        WRITE(6,429) TOLER
        WRITE(6,428) DELT,A,B,C
        WRITE(6,427)
        WRITE(6,433) TDIFE
        WRITE(6,422)
        WRITE(6,431)
        DO 131 I=1,NPOINT
        WRITE(6,430) PRES(I),BRATE(I)
        PRES(I) = PRES(I)/PEQ
  131   CONTINUE
        WRITE(6,209)
C
C         THE TIME AT WHICH THE IGNITER NOZZLE UNCHOKES IS
C        NONDIMENSIONALIZED
C
        UCHOKE = UCHOKE/TREF
```

```
      N = 1
C
C     N ADVANCING CORRESPONDS TO ADVANCING TIME
C
C     N=1
C
C
C        THE FIRST POINTS ARE CALCULATED AND VALUES PRINTED OUT
C
      CALL FLOIG
      CALL NXTPNT(JXYZ)
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME
      LINES = 1
      N = 2
      K = 1
C
C     N GREATER THAN 1
C
 46   CONTINUE
C
C        TIME IS INCREMENTED
C
      TAU = TAU + DELT
      CALL FLOIG
      CALL NXTPNT(JXYZ)
      IF(JXYZ.NE.0) GO TO 111
C
C     SELECTION OF THE ELEMENT OF SURFACE TO WHICH HEAT IS TRANSFERRED
C
      NOS = (S(K) + 1.D-4)/DELX
      NOS = NOS + 1
      GO TO 5
 15   CONTINUE
      IF (DABS(S(K)-0.01D0).GT.1.D-4) GO TO 1
C
C        WHEN 1% OF THE GRAIN IS IGNITED, THE GRAIN STEP-SIZE, DELX, IS
C       INCREASED TO 0.01
C
      DELX = 1.D-2
 1    CONTINUE
      NOS = (S(N) + 1.D-4)/DELX
      NOS = NOS + 1
 5    CONTINUE
      IF(S(K).LE.0.999D0) GO TO 25
C
C        IF S(1) = 1. , THIS TRANSFERS CONTROL TO THE CHAMBER-FILLING
C       PORTION OF THE PROGRAM
C
      X = 1.D0
      GO TO 24
```

```
 25   CONTINUE
      CALL WARUM
C
C     TEST FOR IGNITION
C
      IF(TS-TIG)23,24,24
C
C     IF THE ELEMENT HAS NOT YET IGNITED -- CALCULATE THE PRESENT
C     CHAMBER CONDITIONS, ADVANCE TIME BY A DELT (BY GOING TO 10
C     -- ADVANCING THE LOOP INDEX, N, BY ONE), AND THEN EXAMINING THE
C     ELEMENT AGAIN
C
 23   CONTINUE
C
C       IF THE ELEMENT HAS NOT IGNITED, THE CURRENT SURFACE BURNING
C      AREA IS EQUAL TO THE PREVIOUS VALUE
C
      S(N) = S(K)
C
C        THIS IS A CHECK TO SEE IF A HANGFIRE HAS OCCURRED
C
      IF (S(N).GT.TOLER) CALL RUNCHK(JXYZ,S,N,DPDT)
      IF(JXYZ.EQ.981) GO TO 111
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME,SURFUS(K),REXOMU(N),CONDUC(N)
      LINES = LINES + 1
      IF (LINES-55) 10,701,701
 701  WRITE(6,209)
      LINES = 0
      GO TO 10
C
C     IF THE ELEMENT HAS IGNITED -- PRINT THE PREVIOUS CHAMBER
C     CONDITIONS WITH THE NEW AREA, AND THEN LOOK AT THE NEXT ELEMENT
C     (BY GOING TO 15).  DO NOT ADVANCE TIME.
C
 24   CONTINUE
      S(N) = X
      S(K) = X
      WRITE(6,210) TAU,P(N),S(N),TEMP(N),QM,QMSURF,GIM,DPDT,DTDT,TS,ITN,
     1TIME,SURFUS(K),REXOMU(N),CONDUC(N)
      LINES = LINES + 1
      IF (LINES-55) 850,851,851
 851  WRITE(6,209)
      LINES = 0
 850  CONTINUE
C
C     TEST FOR END OF FLAME SPREADING
C
      IF(S(N)-0.999D0) 15,28,28
 10   CONTINUE
      K = N
      N = N + 1
      GO TO 46
```

```
C
C       S=1
C
C       SINCE S=1, CHAMBER FILLING NOW BEGINS
C
 28     CONTINUE
        SY = 1.DO
        WRITE(6,218)
        WRITE(6,209)
        LINES = 0
C
C       DOUBLING OF STEP SIZE --
C
        DELT = 2.DO*DELT
C
C       PREPARE DATA FOR CHAMBER FILLING
C
        PLAL = P(N)
        TLAL = TEMP(N)
C
C          SINCE THE TIME INCREMENT HAS BEEN DOUBLED, THE VALUES REQUIRED
C         BY THE PREDICTOR-CORRECTOR METHOD ARE TWO INCREMENTS BACK IN
C         TIME
C
        PLALM1 = P(N-2)
        TLALM1 = TEMP(N-2)
        S(N) = 1.DO
        S(K) = 1.DO
C
C       CHAMBER FILLING CALCULATIONS
C
 32     CONTINUE
C
C          TIME IS INCREMENTED
C
        TAU = TAU + DELT
        K = N
        N = N + 1
        CALL FLOIG
        CALL NXTPNT(JXYZ)
C
C          THIS CHECKS FOR THE CONVERGENCE OF THE INTEGRATION. IF CONVER-
C         GENCE HAS NOT OCCURRED, GO TO THE NEXT RUN
C
        IF(JXYZ.NE.0) GO TO 111
        P(N) = PY
        S(N) = SY
        TEMP(N) = TEMPY
        WRITE(6,211)TAU,PY,SY,TEMPY,GIM,DPDT,DTDT,ITN,TIME
        LINES = LINES + 1
        IF (LINES-55) 852,853,853
 853    WRITE(6,209)
        LINES = 0
 852    CONTINUE
        KOUNT = KOUNT + 1
```

```
C
C       TEST FOR END OF IGNITION TRANSIENT  (I.E. ATTAINMENT OF
C       EQUILIBRIUM PRESSURE)
C
C
C          IF THE NUMBER OF CALCULATIONS HAS EXCEEDED 9000 OR
C         IF |DPDT| < 0.01 AND IF THE PRESSURE IS WITHIN 1% OF ITS
C         EQUILIBRIUM VALUE, TERMINATE THE RUN
C
       IF ((KOUNT.GT.9000).OR.((DABS(PY-1.D0).LE.1.D-2).AND.(DABS(DPDT).L
      1E.1.D-2))) GO TO 34
       GO TO 32
  34   CONTINUE
       WRITE(6,991) N
       WRITE(6,990)
       WRITE(6,990)
 111   CONTINUE
       STOP
       END
```

```
      SUBROUTINE RUNCHK(J,S,N,DPDT)
      DIMENSION S(2000)
      DOUBLE PRECISION          S,  DPDT
      J = 0
C
C        IF S HAS INCREASED BETWEEN TIMES (N-2) AND (N), RESET THE
C       COUNTER. IF NOT, INCREMENT THE COUNTER BY ONE.
C
      IF((S(N)-S(N-2)).GT.1.D-6) GO TO 40
      K = K + 1
      IF((K.LT.100).OR.(DPDT.GT.0.D0)) RETURN
      WRITE(6,3)
 3    FORMAT(1H0,20X,20(1H*),' HANGFIRE -- EXECUTION OF THIS RUN TERMINA
     1TED',1X,20(1H*))
C
C        J IS THE HANGFIRE INDICATOR. IF J=981, A HANGFIRE HAS OCCURRED
C       AND THE RUN IS TERMINATED.
C
      J = 981
 40   CONTINUE
      K = 1
      RETURN
      END
```

```
      SUBROUTINE NXTPNT(JXYZ)
C
C     SUBROUTINE INTEGRATES THE DIFFERENTIAL EQUATIONS USING A
C     PREDICTOR-CORRECTOR METHOD
C
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION PRES(100),BRATE(100),RATE(99)
      DOUBLE PRECISION      TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,   GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,  DTDT,    AN,
     4  TOLER,     PY,ETPRES,  TFLME,  PLAL,   TLAL,PLALM1,TLALM1, CONST,
     5   BCON,   SCON,CSTARI,      A,     B,      C,     D,     TO,PRODEN,
     6     AS,      E,      R,  TIME,  RXTX,    QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   CHAR,   FLEQ, TIGNN,VISCOS,   XLAS,  TIG4,
     9   PRES, BRATE,   RATE,    REQ, RENUK, XLAMG
      DOUBLE PRECISION     GIMOFL,    THA,   TNM1,   PNEW,   TNEW, DPNEW,
     1 DTNEW, DPDTL, DTDTL,   POLD,   TOLD, PPRED, TPRED,   PNM1,   PNM2,
     2   TNM2,     PZ,     X1,     X2,     X3,     X4,     X5,     X6,WAITAV,
     3PRINCE,     PN
      DOUBLE PRECISION      DSQRT,   DABS,   DEXP,DFLOAT,   DLOG
      COMMON  RENUK, XLAMG, TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,   GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,  DTDT,    AN,
     4  TOLER,     PY,ETPRES,  TFLME,  PLAL,   TLAL,PLALM1,TLALM1, CONST,
     5   BCON,   SCON,CSTARI,      A,     B,      C,     D,     TO,PRODEN,
     6     AS,      E,      R,  TIME,  RXTX,    QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   FLEQ, TIGNN,   XLAS,   TIG4,
     9   PRES, BRATE,   RATE,    REQ,PREEXP
      COMMON       N,      K,    NOS,    ITN
      COMMON NPOINT
C
C  X1,X2,X3,X4,X5,X6 ARE DUMMY VARIABLES; THEIR VALUES THE COMPUTER
C  OBTAINS FROM WHERE THE FUNCTIONS ARE USED.
C
      PRINCE(X1,X2) = DABS(1.D0 - X1/X2) - TOLER
      WAITAV(X3,X4,X5,X6) = (X3*X4 + X5*X6)/(X4 + X6)
C
C        GIMOFL IS THE NONDIMENSIONAL IGNITER FLOW RATE
C
      GIMOFL = GIM/FLEQ
      IF (N-2) 5,15,20
C
C     S LESS THAN 1
C
C     INITIAL CONDITIONS -- N=1
C
```

```
 5     CONTINUE
       ETPRES = 0.DO
       ETTEMP = 0.DO
       THA = DSQRT(TEMP(1))
       SURFUS(1) = S(1)*PN(P(1))
       VISCOS = WAITAV(XMUG,SURFUS(1),XMUGI,GIMOFL)
       REXOMU(1) = REXEQ/VISCOS
       CONDUC(1) = WAITAV(XLAMG,SURFUS(1),XLAMGI,GIMOFL)*RXTX
       DPDT = GAMMA*(SURFUS(1) - P(1)*THA + PMIG)
       DTDT = TEMP(1)*((GAMMA-TEMP(1))*SURFUS(1)/P(1)-(GAMMA-1.DO)*THA
      1+TMIG/P(1))
       RHELP(1)=(DPDT-P(1)*DTDT/TEMP(1))/TEMP(1)
C
C         THE FIRST POINT HAS BEEN CALCULATED. CONTROL IS RETURNED TO THE
C        MAIN PROGRAM
C
       RETURN
C
C      N=2  THE SECOND POINT IS CALCULATED USING A MODIFIED RUNGE-KUTTA
C      SCHEME.
C
 15    CONTINUE
C
C         THIS ESTIMATES THE SECOND SET OF POINTS
C
       PNEW = P(K) + DELT*DPDT
       TNEW = TEMP(K) + DELT*DTDT
       THA = DSQRT(TNEW)
C      SURFUS IS THE NON-DIMENSIONAL MASS FLUX FROM THE SURFACE OF THE
C         PROPELLANT.
       SURFUS(K) = S(K)*PN(PNEW)
       VISCOS = WAITAV(XMUG,SURFUS(K),XMUGI,GIMOFL)
       REXOMU(N) = REXEQ/VISCOS
       CONDUC(N) = WAITAV(XLAMG,SURFUS(K),XLAMGI,GIMOFL)*RXTX
       DPNEW = GAMMA*(SURFUS(K) - PNEW*THA + PMIG)
       DTNEW=TNEW*((GAMMA-TNEW)*SURFUS(K)/PNEW-(GAMMA-1.DO)*THA+TMIG/PNEW
      1)
       P(N) = P(K) + DELT/2.DO*(DPDT + DPNEW)
       TEMP(N) = TEMP(K) + DELT/2.DO*(DTDT + DTNEW)
       DPDT=DPNEW
       DTDT=DTNEW
       RHELP(N)=(DPDT-P(N)*DTDT/TEMP(N))/TEMP(N)
       RETURN
C
C
C         THE FIRST TWO POINTS HAVE BEEN CALCULATED. NOW THE PREDICTOR-
C        CORRECTOR METHOD CAN BE USED
```

```
C       N GREATER THAN TWO
C       TEST FOR END OF FLAME SPREADING
C
 20     IF (S(K) - 0.999D0) 21,80,80
 21     CONTINUE
        ITN = 0
        DPDTL = DPDT
        DTDTL = DTDT
C
C       THE PREDICTOR----
C
        POLD = P(N-2) + 2.D0*DELT*DPDTL
        TOLD = TEMP(N-2) + 2.D0*DELT*DTDTL
        PPRED = POLD
        TPRED = TOLD
 55     CONTINUE
        THA = DSQRT(TOLD)
        SURFUS(K) = S(K)*PN(POLD)
        VISCOS = WAITAV(XMUG,SURFUS(K),XMUGI,GIMOFL)
        REXOMU(N) = REXEQ/VISCOS
        CONDUC(N) = WAITAV(XLAMG,SURFUS(K),XLAMGI,GIMOFL)*RXTX
        DPDT = GAMMA*(SURFUS(K) - POLD*THA + PMIG)
        DTDT=TOLD*((GAMMA-TOLD)*SURFUS(K)/POLD-(GAMMA-1.D0)*THA+TMIG/POLD)
C
C          THESE ARE THE PREDICTED VALUES. THEY ARE NOW CORRECTED
C
C
C       THE CORRECTOR ---
C
        P(N) = P(K) + DELT/2.D0*(DPDTL + DTDT)
        TEMP(N) = TEMP(K) + DELT/2.D0*(DTDTL + DTDT)
C
C       TEST FOR CONVERGENCE OF INTEGRATION
C
        IF (PRINCE(POLD,P(N))) 62,60,60
 62     IF (PRINCE(TOLD,TEMP(N))) 65,60,60
 60     IF(ITN-10)61,96,96
 61     CONTINUE
        POLD = P(N)
        TOLD = TEMP(N)
        ITN = ITN+1
        GO TO 55
C       ETPRES AND ETTEMP ARE THE TRUNCATION ERRORS ACCUMULATED DURING
C       THE INTEGRATION ITERATIONS, ON THE PRESSURE AND TEMP, RESPECTIVELY
 65     CONTINUE
        P(N) = P(N) + ETPRES
        TEMP(N) = TEMP(N) + ETTEMP
        ETPRES = 2.D-1*(PPRED-P(N))
        ETTEMP = 2.D-1*(TPRED-TEMP(N))
        RHELP(N) = (DPDT-P(N)*DTDT/TEMP(N))/TEMP(N)
        RETURN
```

```
C      S EQUALS ONE -- CHAMBER FILLING INTERVAL
C      INTEGRATING SCHEME SAME AS BEFORE
C      PNM1, PNM2 ARE THE TWO PREVIOUS POINTS.  POLD STARTS AS THE
C      PREDICTED PRESSURE, THEN IS ITERATED WITH PY IN THE CORRECTOR
C      FORMULA.
 80    CONTINUE
       PNM1 = PLAL
       TNM1 = TLAL
       PNM2 = PLALM1
       TNM2 = TLALM1
       PZ = PN(PNM1)
       THA = DSQRT(TNM1)
       DPDTL = GAMMA*(PZ - PNM1*THA + PMIG)
       DTDTL=TNM1*((GAMMA-TNM1)*PZ/PNM1-(GAMMA-1.)*THA+TMIG/PNM1)
       ITN = 0
       POLD = PNM2 + 2.D0*DELT*DPDTL
       TOLD = TNM2 + 2.D0*DELT*DTDTL
       PPRED = POLD
       TPRED = TOLD
 85    CONTINUE
       PZ = PN(POLD)
       THA = DSQRT(TOLD)
       CALL FLOIG
       DPDT = GAMMA*(PZ - POLD*THA + PMIG)
       DTDT = TOLD*((GAMMA-TOLD)*PZ/POLD-(GAMMA-1.D0)*THA + TMIG/POLD)
       PY = PNM1 + DELT/2.D0*(DPDTL + DPDT)
       TEMPY = TNM1 + DELT/2.D0*(DTDTL + DTDT)
       IF (PRINCE(POLD,PY)) 92,90,90
 92    IF (PRINCE(TOLD,TEMPY)) 95,90,90
 90    IF(ITN-10) 91,96,96
 96    CONTINUE
       WRITE(6,250)
 250   FORMAT(1H0,20(1H*),87HPREDICTOR-CORRECTOR SCHEME HAS NOT CONVERGED
      1 AFTER 10 ITERATIONS; EXECUTION TERMINATED ,20(1H*)/)
       JXYZ = 1200
       RETURN
```

```
 91   CONTINUE
      POLD = PY
      TOLD = TEMPY
      ITN = ITN + 1
      GO TO 85
C
C        THE ABOVE FIVE STATEMENTS RESTART THE CORRECTOR CYCLE
C
 95   CONTINUE
      PY = PY + ETPRES
      TEMPY = TEMPY + ETTEMP
      ETPRES = 0.2D0*(PPRED-PY)
      ETTEMP = 0.2D0*(TPRED-TEMPY)
C     STORAGE OF LAST TWO POINTS FOR NEXT TIME AROUND
      PLAL = PY
      TLAL = TEMPY
      PLALM1 = PNM1
      TLALM1 = TNM1
      RETURN
      END
```

```
      SUBROUTINE WARUM
C     SUBROUTINE CALCULATES THE TEMPERATURE AT A GIVEN STATION BY
C     INTEGRATING THROUGH TIME THE HEAT TRANSFERRED TO IT
C     THE INTEGRATION IS DONE BY SUMMING AREAS.  THE AREAS ARE EVALUATED
C     AT THE MIDDLE OF THE INTERVAL SO THAT ERRORS TEND TO CANCEL.
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION PRES(100),BRATE(100),RATE(99)
      DIMENSION POTHAF(2000),SQ(2000)
      LOGICAL SAMEAR
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ, RENUK, XLAMG
      DOUBLE PRECISION     POTHAF,  TINT,    SQ,ONEMIX,   SUM,    Q1,
     1 TERM1, TERM2,  DIFF
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ,PREEXP
      COMMON       N,     K,   NOS,   ITN
      COMMON NPOINT
C
C    THE SURFACE HEAT RELEASE EQUATION HAS THE FORM
C      QMSURF = Q*PRODEN*AS*EXP(-E/(R*(TS + 273.15))) , WHERE
C    Q IS AN EMPIRICAL CONSTANT, PRODEN IS THE PROPELLANT DENSITY, AS IS
C   A DIMENSIONALIZING BURNING RATE FOR THE EXPONENTIAL TERM, E IS THE
C   ACTIVATION ENERGY OF THE PROPELLANT, R IS THE UNIVERSAL GAS CONSTANT,
C   AND TS IS THE TEMPERATURE OF THE SURFACE OF THE PROPELLANT, IN
C   DEGREES CENTIGRADE.
C
C
C         X IS THE GRAIN ELEMENT BEING EXAMINED
C
      X = DFLOAT(NOS)*DELX
      POTHAF(K) = P(K)/DSQRT(TEMP(K))
      IF(DFLOAT(K)*DELT.GT.UCHOKE) GO TO 150
      CHAR = TREF
      GO TO 200
  150 CONTINUE
      CHAR = TREF1
  200 CONTINUE
```

```
C
C         THE CHARACTERISTIC TIME TO BE USED IS DETERMINED BY WHETHER OR
C       NOT THE IGNITER HAS UNCHOKED
C
      SQ(K) = DSQRT(CHAR/TAU)
      IF(DABS(XLAS-X).GT.TOLER) GO TO 5
C
C         IF X IS THE SAME AS THE PREVIOUS VALUE, THE FOLLOWING
C       CALCULATIONS CAN BE OMITTED
C
      REX = REXOMU(K)*ALPLSX*(POTHAF(K) + ONEMIX*RHELP(K))
      QMCONV(K) = CONDUC(K)/ALPLSX*REX**RENUX
C
C         SAMEAR = 'SAME AREA'
C
      SAMEAR = .TRUE.
      GO TO 30
 5    CONTINUE
      ALPLSX = ALPLSX + DELX
      ONEMIX = 1.DO - X
      SAMEAR = .FALSE.
C
C         NOW WE ARE AT A NEW AREA
C
 30   CONTINUE
      SUM = 0.DO
      REX = REXEQ*ALPLSX*(POTHAF(1)+ONEMIX *RHELP(1))/XMUGI
C        SCON = RENUK*XLAMG*(TCIG*TFLME-273.15)/XL
      Q1 = SCON*REX**RENUX/ALPLSX
      QM = Q1
      TERM1 = DSQRT(TREF/TAU)*QM
      SUM = DELT*TERM1
      QMSURF = 0.DO
      DIFF = TAU
      IF (N - 3) 35,10,10
 10   CONTINUE
C
C         THIS LOOP INTEGRATES THE HEAT FLUX THROUGH TIME TO GET THE
C       SURFACE TEMPERATURE
C
C     HERE ADVANCING M CORRESPONDS TO ADVANCING TIME.
C
```

```
      DO 20 M=2,K
      DIFF = DIFF - DELT
C
C        IF THE SAME X AS IN THE PREVIOUS PASS THROUGH THE SUBROUTINE IS
C       BEING EXAMINED, THE NEXT TWO STATEMENTS ARE BYPASSED
C
      IF (SAMEAR) GO TO 40
      REX = REXOMU(M)*ALPLSX*(POTHAF(M) + CNEMIX*RHELP(M))
      QMCONV(M) = CONDUC(M)/ALPLSX*REX**RENUX
 40   CONTINUE
      QM = QMCONV(M) + QMSURF
      TERM2 = SQ(N-M)*QM
      TINT = (TERM2 + TERM1)/2.DO
      TERM1 = TERM2
      SUM = SUM + DELT*TINT
      TS = THERM*SUM
C
C        IF THE SURFACE TEMPERATURE IS LESS THAN 40% OF THE IGNITION
C       TEMPERATURE, THE SURFACE HEAT RELEASE TERM NEED NOT BE
C       CALCULATED
C
      IF(TS.LT.TIG4) GO TO 20
C        QPA = Q*PRODEN*AS
C  EOVERR = -E/R .
C  SAVEXX = 273.15 + TSO
      QMSURF = QPA*DEXP(EOVERR/(TS+SAVEXX))
 20   CONTINUE
      TINT = DSQRT(2.DO*CHAR/DELT)*QM
      SUM = SUM + DELT*TINT
 35   CONTINUE
      TS = TSO + THERM*SUM
      XLAS = X
      RETURN
      END
```

```
      SUBROUTINE FLOIG
C     SUBROUTINE SUPPLIES THE IGNITER EFFECTS
C  'T' IS THE REAL TIME, IN SECONDS.
C  THE NEXT THREE STATEMENTS EXPRESS THE IGNITER MASS FLOW RATE AS A
C FUNCTION OF TIME--THE SECOND STATEMENT, WHICH IS A QUADRATICALLY
C DECREASING FUNCTION, USING THE FOLLOWING AS INPUT CONSTANTS... A,B,C,
C D,TO.
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION PRES(100),BRATE(100),RATE(99)
      DOUBLE PRECISION      TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,   GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,   DTDT,    AN,
     4  TOLER,     PY,ETPRES,  TFLME,   PLAL,   TLAL,PLALM1,TLALM1,  CONST,
     5   BCON,   SCON,CSTARI,      A,      B,      C,      D,    TO,PRODEN,
     6     AS,      E,      R,   TIME,   RXTX,    QPA,UCHOKE,  TREF1,   FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   CHAR,   FLEQ,  TIGNN,VISCOS,   XLAS,   TIG4,
     9   PRES,  BRATE,   RATE,    REQ, RENUK,  XLAMG
      DOUBLE PRECISION      DSQRT,   DABS,   DEXP,DFLOAT,   DLOG
      COMMON   RENUK, XLAMG, TDIFE,      X,     XL,ALPLSX,    REX, RENUX,
     1      Q,   DELT,   TREF,     AT,    TSO, THERM,     TS,    TAU,  TCIG,
     2   TEMP, GAMMA,   PMIG,   TMIG, TEMPY,   ATIG,    PEQ, CSTAR,   GIM,
     3      S,     SY,   DELX, REXEQ,      P, RHELP,   DPDT,   DTDT,    AN,
     4  TOLER,     PY,ETPRES,  TFLME,   PLAL,   TLAL,PLALM1,TLALM1,  CONST,
     5   BCON,   SCON,CSTARI,      A,      B,      C,      D,    TO,PRODEN,
     6     AS,      E,      R,   TIME,   RXTX,    QPA,UCHOKE,  TREF1,   FLOW,
     7DELREF,     QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,   XMUG,QMCONV,   FLEQ,  TIGNN,   XLAS,   TIG4,
     9   PRES,  BRATE,   RATE,    REQ,PREEXP
      COMMON       N,      K,    NOS,    ITN
      COMMON NPOINT
      IF(TAU.LT.UCHOKE) GO TO 800
C
C        IF THE IGNITER HAS UNCHOKED, THE CHARACTERISTIC TIME HAS
C       INCREASED DUE TO THE ADDITIONAL VOLUME
C
      TIME = UCHOKE*TREF + (TAU - UCHOKE)*TREF1
      GO TO 801
  800 CONTINUE
      TIME = TAU*TREF
  801 CONTINUE
      IF (TIME.LT.TO) GIM = FLOW
      IF ((TIME.GT.TO).AND.(TIME.LT.D)) GIM = C + TIME*(B + TIME*A)
      IF (TIME.GT.D) GIM = 0.0
      PMIG = TIGNN*GIM/FLEQ
      IF (N.EQ.1) GO TO 901
      TMIG = PMIG/TIGNN*(GAMMA*TIGNN - TEMP(K))
      RETURN
  901 CONTINUE
      TMIG = PMIG/TIGNN*(GAMMA*TIGNN - TEMP(1))
      RETURN
      END
```

```
      SUBROUTINE QUADRA(A,B,C,D,TO,FLOW,UCHOKE)
C  GIVEN THREE POINTS AS INPUT, THIS SUBROUTINE CALCULATES THE COEFFI-
C  CIENTS IN THE QUADRATIC EXPRESSION FOR THE IGNITER TAIL-OFF IN
C  SUBROUTINE 'FLOIG'.
      DOUBLE PRECISION          X,     Y,     A,     B,     C,     Z,
     1     D,    TO,  FLOW,UCHOKE
      DIMENSION X(3),Y(3)
      READ(5,100) X,Y,UCHOKE
  100 FORMAT(8F10.0)
      Z = (Y(2)-Y(1))/(X(2)-X(1))
      A = ((Y(3)-Y(1))/(X(3)-X(1))-Z)/(X(3)-X(2))
      B = Z-A*(X(2)+X(1))
      C = Y(1)-A*X(1)**2-B*X(1)
      FLOW = Y(1)
      TO = X(1)
      D = X(3)
      RETURN
      END
```

```
      REAL FUNCTION PN*8(PR)
      DIMENSION S(2000),P(2000),TEMP(2000),RHELP(2000),REXOMU(2000),
     1CONDUC(2000),SURFUS(2000),QMCONV(2000)
      DIMENSION PRES(100),BRATE(100),RATE(99)
      DOUBLE PRECISION      TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  CHAR,  FLEQ, TIGNN,VISCOS,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ, RENUK, XLAMG
      DOUBLE PRECISION         PR
      DOUBLE PRECISION      DSQRT,  DABS,  DEXP,DFLOAT,  DLOG
      COMMON  RENUK, XLAMG, TDIFE,     X,    XL,ALPLSX,   REX, RENUX,
     1     Q,  DELT,  TREF,    AT,   TSO, THERM,    TS,   TAU,  TCIG,
     2  TEMP, GAMMA,  PMIG,  TMIG, TEMPY,  ATIG,   PEQ, CSTAR,   GIM,
     3     S,    SY,  DELX, REXEQ,     P, RHELP,  DPDT,  DTDT,    AN,
     4 TOLER,    PY,ETPRES, TFLME,  PLAL,  TLAL,PLALM1,TLALM1, CONST,
     5  BCON,  SCON,CSTARI,     A,     B,     C,     D,    TO,PRODEN,
     6    AS,     E,     R,  TIME,  RXTX,   QPA,UCHOKE, TREF1,  FLOW,
     7DELREF,    QM,QMSURF,EOVERR,SURFUS,XLAMGI,XMUGI ,SAVEXX,CONDUC,
     8REXOMU,  XMUG,QMCONV,  FLEQ, TIGNN,  XLAS,  TIG4,
     9  PRES, BRATE,  RATE,   REQ,PREEXP
      COMMON       N,     K,   NOS,   ITN
      COMMON NPOINT
      I = 0
2     CONTINUE
      I = I + 1
      IF ((PR-PRES(I)).LT.0.D0) GO TO 1
      IF (I.LT.NPOINT) GO TO 2
1     CONTINUE
      IF (I.EQ.1) GO TO 3
      PN = BRATE(I)*(PR/PRES(I))**RATE(I-1)
      GO TO 5
3     CONTINUE
      PN = BRATE(1)*(PR/PRES(1))**RATE(1)
5     CONTINUE
      PN = PN/REQ
      RETURN
      END
```